

ADA138097



# COMPUTER MODELING AND EXPERIMENTAL VALIDATION OF LOSSES IN A STRIP GEOMETRY EXPLOSIVE MAGNETIC FLUX COMPRESSION GENERATOR

## THEESIS

AFIT/GE/EE/83D-28

**DISTRIBUTION STATEMENT A**  
Approved for public release  
Distribution Unlimited

DTIC  
ELECTED  
FEB 22 1984

**DEPARTMENT OF THE AIR FORCE  
AIR UNIVERSITY**

AIR FORCE INSTITUTE OF TECHNOLOGY

## Wright-Patterson Air Force Base, Ohio

84 02 21 191

AFIT/GE/EE/83D-28

COMPUTER MODELING AND EXPERIMENTAL VALIDATION  
OF LOSSES IN A STRIP GEOMETRY EXPLOSIVE  
MAGNETIC FLUX COMPRESSION GENERATOR

THESIS

Mary P. Jeffrey                    James L. Hebert  
First Lieutenant, USAF    Second Lieutenant, USAF

AFIT/GE/EE/83D-28

Approved for public release; distribution unlimited

DTIC  
ELECTED  
FEB 22 1984  
S B D

COMPUTER MODELING AND EXPERIMENTAL VALIDATION  
OF LOSSES IN A STRIP GEOMETRY EXPLOSIVE  
MAGNETIC FLUX COMPRESSION GENERATOR

THESIS

Presented to the Faculty of the School of Engineering  
of the Air Force Institute of Technology  
Air University  
In Partial Fulfillment of the  
Requirements for the Degree of  
Master of Science in Electrical Engineering

Mary P. Jeffrey, B.S.  
First Lieutenant, USAF

James L. Hebert, B.S.  
Second Lieutenant, USAF

December 1983

Approved for public release; distribution unlimited

Preface

The purpose of this thesis was to develop and validate a computer model of strip geometry explosive flux compression generator. The Air Force Weapons Laboratory had designed a strip generator and conducted preliminary familiarization experiments with it. A computer program to predict generator output was developed. This computer model was then validated using the AFWL strip generator.

We would like to thank our advisor, Major Timothy L. Skvarenina of the Air Force Institute of Technology at Wright-Patterson AFB, Ohio for his assistance during this project. We are especially grateful to Dr. Robert E. Reinovsky of the Air Force Weapons Laboratory at Kirtland AFB, New Mexico. His guidance and assistance were extremely helpful. We are also grateful to Wally Kaiser of Maxwell Labs at Kirtland AFB, New Mexico. His technical knowledge and enthusiastic support made the experiments both enjoyable and highly productive.

This effort was jointly funded by the Air Force Weapons Laboratory and the Defense Nuclear Agency.

Accession For	
NTIS GRA&I	<input checked="" type="checkbox"/>
DTIC TAB	<input type="checkbox"/>
Unannounced	<input type="checkbox"/>
Justification	
By	
Distribution/	
Availability Codes	
Dist	Avail and/or Special
A-1	



## Table of Contents

	Page
Preface . . . . .	ii
List of Figures . . . . .	v
List of Tables . . . . .	vii
Abstract . . . . .	viii
I. Introduction . . . . .	1
Background . . . . .	1
Problem . . . . .	2
Scope . . . . .	3
Assumptions . . . . .	3
General Approach . . . . .	4
Computer Model . . . . .	4
Experimental Validation . . . . .	5
II. Basic Theory . . . . .	8
Equivalent Circuit Modeling . . . . .	8
Time Varying Inductance . . . . .	9
Time Varying Resistance . . . . .	9
Constant Resistance Model . . . . .	11
Empirical Modeling . . . . .	11
III. Computer Model . . . . .	14
Theoretical Models . . . . .	14
Flux Conserved Model . . . . .	14
Time Varying Resistance Model . . . . .	18
Empirical Models . . . . .	22
Sliding Contact Model . . . . .	22
Changing Area Loss Model . . . . .	24
Efficiency Model . . . . .	26
IV. Experimental Apparatus . . . . .	28
Major Components . . . . .	28
Capacitor Bank . . . . .	28
Closing Switch . . . . .	28
Firing System . . . . .	30
Transmission Line . . . . .	30
Diagnostics . . . . .	31
Rogowski Coils . . . . .	31
Voltage Probes . . . . .	33
Oscilloscopes . . . . .	34

	Page
<b>V. Experimental Procedures . . . . .</b>	<b>35</b>
General Procedures . . . . .	35
Diagnostic Line Tests . . . . .	35
X Unit and Detonation Line Test . . . . .	36
Preparation of the Oscilloscopes . . . . .	36
Line Short Shots . . . . .	36
MCG Short Shots . . . . .	38
MCG Shots . . . . .	40
<b>VI. Results and Conclusions . . . . .</b>	<b>43</b>
Results . . . . .	43
Computer Model Results . . . . .	45
Flux Conserved Model . . . . .	45
Resistance Model . . . . .	48
Sliding Contact Model . . . . .	50
Changing Area Loss Model . . . . .	50
Flux Trapping Efficiency Model . . . . .	57
General Results . . . . .	57
Conclusions . . . . .	60
Recommendations . . . . .	60
<b>Appendix A . . . . .</b>	<b>62</b>
Inputs . . . . .	63
Outputs . . . . .	63
<b>Appendix B . . . . .</b>	<b>85</b>
<b>Bibliography . . . . .</b>	<b>112</b>
<b>Vita . . . . .</b>	<b>113</b>

## List of Figures

Figure	Page
1-1 Air Force Weapons Laboratory's MCG . . . . .	2
1-2 Experimental Set Up . . . . .	6
2-1 Equivalent Electrical Circuit . . . . .	8
2-2 Slipping Loss Surfaces . . . . .	11
3-1 Asymmetric Sandwich . . . . .	15
3-2 Compression of Generator . . . . .	16
3-3 Generator Ceasation . . . . .	17
3-4 Slipping Model Match Points . . . . .	24
4-1 MCG Experimental Set Up . . . . .	29
4-2 Placement of Test Diagnostic Devices . . . . .	32
5-1 Typical Short Circuit Plot . . . . .	37
6-1 Experimental Current Test 1 . . . . .	44
6-2 Time Varying Inductance . . . . .	46
6-3 Equivalent Circuit Currents Test 1 . . . . .	47
6-4 Time Varying Resistance Test 1 . . . . .	49
6-5 S Curve Test 1 . . . . .	51
6-6 Slipping Currents Test 1 . . . . .	52
6-7 Additional Area Test 1 . . . . .	54
6-8 Changing Areas Test 1 . . . . .	55
6-9 Changing Area Currents Test 1 . . . . .	56
6-10 Efficiency Test 1 . . . . .	58
6-11 Efficiency Currents Test 1 . . . . .	59
A-1 Computer Inputs . . . . .	62
A-2 Load Geometries . . . . .	64

Figure	Page
B-1 Experimental Current Test 2 . . . . .	86
B-2 Experimental Current Test 3 . . . . .	87
B-3 Experimental Current Test 4 . . . . .	88
B-4 Experimental Current Test 5 . . . . .	89
B-5 Equivalent Circuit Currents Test 2 . . . . .	90
B-6 Equivalent Circuit Currents Test 3 . . . . .	91
B-7 Equivalent Circuit Currents Test 4 . . . . .	92
B-8 Equivalent Circuit Currents Test 5 . . . . .	93
B-9 Time Varying Resistance Test 2 . . . . .	94
B-10 Time Varying Resistance Test 3 . . . . .	95
B-11 Time Varying Resistance Test 4 . . . . .	96
B-12 Time Varying Resistance Test 5 . . . . .	97
B-13 S Curve Test 2 . . . . .	98
B-14 S Curve Test 3 . . . . .	99
B-15 Slipping Currents Test 2 . . . . .	100
B-16 Slipping Currents Test 3 . . . . .	101
B-17 Additional Area Test 2 . . . . .	102
B-18 Additional Area Test 3 . . . . .	103
B-19 Changing Areas Test 2 . . . . .	104
B-20 Changing Areas Test 3 . . . . .	105
B-21 Changing Area Currents Test 2 . . . . .	106
B-22 Changing Area Currents Test 3 . . . . .	107
B-23 Efficiency Test 2 . . . . .	108
B-24 Efficiency Test 3 . . . . .	109
B-25 Efficiency Currents Test 2 . . . . .	110
B-26 Efficiency Currents Test 3 . . . . .	111

List of Tables

Table	Page
5-1      Summary of Input Conditions . . . . .	42
6-1      Summary of Results . . . . .	45

### Abstract

A computer program to predict the performance of a strip geometry explosive magnetic flux compression generator (MCG) was developed and validated.

The program contains five separate models of the MCG, two theoretical and three empirically based. The first model is a theoretical lossless flux conserved model. The second model accounts for resistive losses due to plate resistance and a flux diffusion equivalent resistance. The first empirical model models the remaining losses as a slipping loss. The second empirical model adjusts the flux conserved model with an additional time varying inductance. The final empirical model is a simple flux trapping efficiency model.

Actual MCG experiments were conducted using the Air Force Weapons Laboratory's strip MCG. The data from these experiments was used to validate the computer program. Input currents varied from 294.0 KA to 1100.0 KA with resulting output currents of 2210.0 KA to 10261.0 KA and current amplification factors between 6.29 and 15.75.

# COMPUTER MODELING AND EXPERIMENTAL VALIDATION OF LOSSES IN A STRIP GEOMETRY EXPLOSIVE MAGNETIC FLUX COMPRESSION GENERATOR

## I. Introduction

Magnetic flux compression generators (MCGs) are devices which create ultrahigh magnetic fields by compressing magnetic fields between two metal surfaces to achieve field multiplication. This field multiplication is achieved by converting chemical energy into electrical energy.

### Background

MCGs have been under investigation since the early 1950s (1:10). Initial experiments were done in strip geometries, explosively driving two plates together. Because experiments in coaxial geometry proved more efficient, attention soon focused on coaxial geometry (2:5191). For many years, the focus remained on the coaxial flux compression generators.

Recently, attention has returned to the strip geometry MCG. Because of their higher current densities and relatively simple construction, the military is now considering strip geometry MCGs as a possible power supply for some of its advanced weapons and experiments (3).

By their nature, explosive MCGs are one shot devices. For this reason, computer models predicting the MCG's output characteristics are beneficial in terms of cost and time of development.

### Problem

The purpose of this thesis was to develop and validate a simple computer model of a strip geometry MCG's operation. The computer model accounts for the major physical processes involved in the MCG's operation. Model validation was done using the Air Force Weapons Laboratory's (AFWL) MCG shown in Figure 1-1.

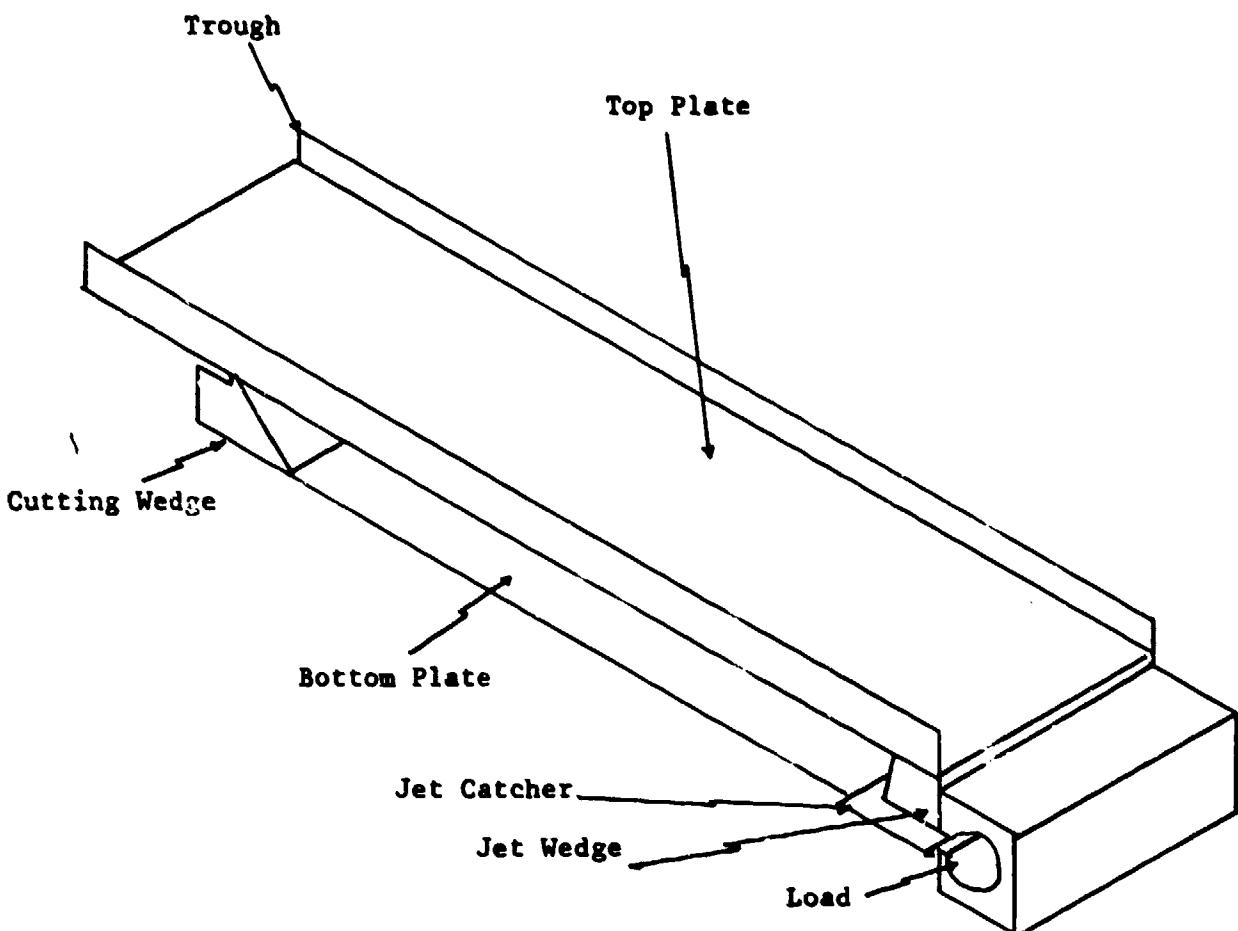


Figure 1-1. Air Force Weapons Laboratory's MCG

### Scope

The study done for this thesis was limited to the design and validation of a computer model of a strip geometry MCG. The loss mechanisms considered were flux diffusion, plate resistance, sliding contact, and incomplete compression.

The criteria used to evaluate the model were the ability to predict the output current as a function of time and the time to peak current amplification.

### Assumptions

In order to model the MCG's operation several basic assumptions were made. These assumptions include:

- 1) The electrical circuit used in the experiments can be modeled by the lumped parameter elements of inductance, capacitance, and resistance (4:327); (This allows the MCG's operation to be described by RLC circuit analysis.);
- 2) The magnetic fields are spatially uniform within the MCG;
- 3) The load and throat inductance of the MCG are constant with time;
- 4) The metal plates are incompressible (5:364);
- 5) The explosive process brings the two plates together in a uniform motion so that the compression can be considered linear (6:7);
- 6) During the compression process, the metal plates offer no resistance to plate motion (6:3); and
- 7) Specific heat remains constant (5:362).

### General Approach

Computer Model. In order to model the generator's operation with an equivalent electrical circuit, basic relationships which describe the physical processes involved had to be developed. The first problem was to determine how the explosive energy was transferred to the metal plates. The detonation of the explosive accelerated the metal plate converting the chemical energy of the explosive to kinetic energy or changing velocity. Although complex computer codes exist to describe this energy conversion, the Gurney method provides a quick, simple approximation for the changing metal velocity (6:3).

The second physical process to be accounted for was the time varying inductance. The changing metal velocity predicts the motion of the metal plates which, in turn, is used to calculate the changing area enclosed by the MCG. From this changing area, a time varying inductance was calculated. Combined with the lumped element parameters determined from the experimental circuit, a totally flux conserved (lossless) model was developed. As the plates are driven together, the inductance decreases, converting kinetic energy to electric energy.

Using this flux conserved model, the flux diffusion losses were calculated. These losses were modeled by a time varying effective resistance. Losses due to the copper's resistance were also computed. This resistance, combined with the effective resistance which accounts for flux diffusion losses, was used to produce a total resistance model of the MCG.

During experimental validation, it was discovered that other physical loss mechanisms were present. These losses had to be

accounted for in order to completely describe the MCG's operation. Three empirical models were developed. The first model which accounts for slipping losses was developed in a manner similar to that of Knoepfel (1:189-191). A second model which allows for compression at rates faster or slower than predicted by the Gurney velocity was also developed. A final model which is based totally on empirical measurements accounts for a flux compression efficiency.

A detailed description of the computer models can be found in Chapter III.

Experimental Validation. Validation of the computer program consisted of performing actual strip MCG experiments. The experimental circuit was set up as shown in Figure 1-2. Constant circuit parameters such as line inductance and resistance were determined by discharging the capacitor bank through a shorted line as well as through the AFWL MCG. Current measurements were used to determine these values.

Several parameters were varied to check the validity of the computer model. These included changing the load impedance, the tamping, the amount of explosive, and the input voltage to the capacitor bank.

Five MCG experiments were successfully performed. Test measurements included voltages across the switch and load, and current derivatives through the switch, line, and load. Currents were obtained by actively integrating the current derivatives. Data was displayed on oscilloscopes photographed with polaroid cameras.

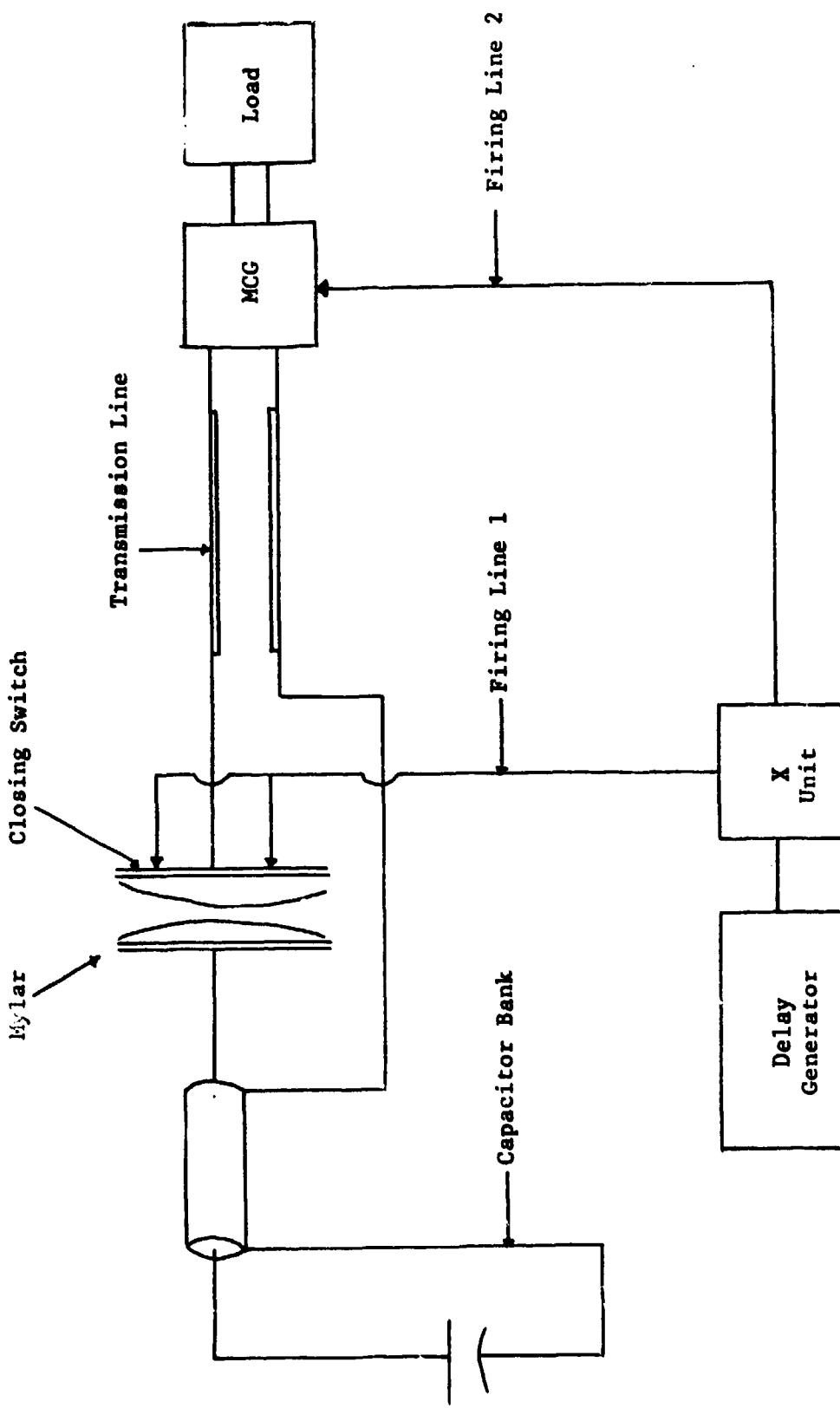


Figure 1-2. Experimental Set Up

A detailed description of the experimental apparatus can be found in Chapter IV. Chapter V describes the experimental procedures used. Finally, the results comparing the experimental data with the computer models, conclusions, and recommendations can be found in Chapter VI.

## II. Basic Theory

Numerous models have been developed to describe MCG operation. The models can be broken down into two major categories, equivalent electrical circuit modeling and empirical modeling.

### Equivalent Circuit Modeling

Many models used to describe MCG operation use an equivalent electrical circuit approach. Each of these models describe MCG operation as having four major components: an input power supply, an inductance, a resistance, and a load inductance. The equivalent circuit is shown below.

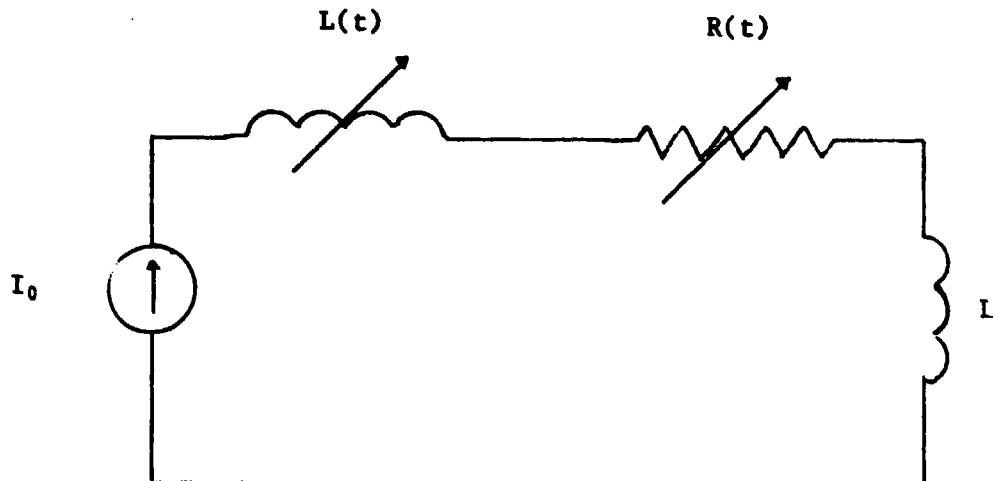


Figure 2-1. Equivalent Electrical Circuit

The input power is generally described as an input current whose value is determined by the input circuitry. The load inductance is

determined by the particular use of the generator. The models all describe the generator inductance as a time varying inductance. They differ in their description of the resistance; some describe it as a time varying resistance while others describe it as a constant.

Time Varying Inductance. Inductance varies as a function of the dimensions of the system. During the compression process, the metal plates are explosively driven together. This drastically alters the dimensions of the system and hence the system inductance. Through a change of variables, this dimensionally changing inductance can be modeled as a time varying inductance (7:147;8:334).

Time Varying Resistance. Experts generally agree that, as a minimum, resistance is a function of resistivity, temperature, and path length (8:334;9:554). Resistivity and temperature are interrelated. As long as the metal plates do not liquify, resistivity can be described as a linear function of temperature (10:393).

$$\rho = \rho_0(1 + k\theta) \quad (2-1)$$

where

$\rho_0$  is the resistivity of the plate at room temperature

$k$  is a constant equal to  $10^{-3}/^{\circ}\text{C}$

$\theta$  is the temperature in  $^{\circ}\text{C}$

A method must then be determined to describe how temperature changes with a known variable. Because the thermal diffusion process is much slower than the magnetic diffusion process, temperature can be described strictly as a function of the magnetic flux density (1:74).

$$\theta = \chi B^2 \quad (2-2)$$

where

$\chi$  is a constant equal to  $1170^{\circ}\text{C}/(\text{MG})^2$

$B$  is the magnetic flux density in megagauss (10:392)

As MCG operation progresses, the magnetic flux is compressed. (A detailed discussion of how the magnetic flux is compressed is contained in Chapter III.) This means that the magnetic flux density and hence the resistivity can be made a function of time through a change of variables. Additionally, the path through which the current flows changes during MCG operation. By using the familiar expression

$$R = \frac{\rho l}{A} \quad (2-3)$$

where

$\rho$  is resistivity

$l$  is path length

$A$  is cross sectional area

The resistance of the plates,  $R_p$ , can be defined as a function of time.

The process of magnetic flux diffusion is modeled in the equivalent electrical circuit approach as a time varying resistance (1:185). By using a skin layer method, a time varying resistance modeling flux diffusion is defined as

$$R = \frac{1}{\sigma_0 \sqrt{\frac{\tau}{\sigma_0 \mu}}} \quad (2-4)$$

where

$\sigma_0$  is conductivity

$\mu_0$  is magnetic permeability

$\tau$  is a characteristic time defined by

$$\tau = \frac{H}{\frac{dH}{dt}} \quad (2-5)$$

Because  $\tau$  is a function of time, magnetic flux diffusion can be modeled as a time varying resistance.

Constant Resistance Model. Experts who model the resistance as a constant during MCG operation realize that resistance does in fact change with time. These changes are small and linear. Thus, they can be modeled as an average resistance (1:83);11:DI-8-3). In this manner, resistance can be modeled as a constant.

#### Empirical Modeling

Empirical models are based on experimental data. Knoepfel suggests that a loss mechanism not modeled by previous methods is a slipping contact loss. Slipping losses occur when plate compression is incomplete and flux is trapped between the plates. For the AFWL generator, this slipping loss occurs on the surfaces shown as a dark line in Figure 2-2.

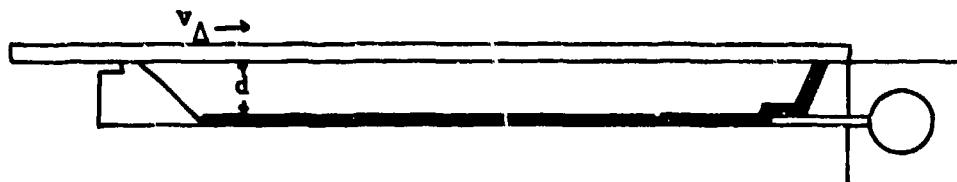


Figure 2-2. Slipping Loss Surfaces

Along these surfaces, the empirical model claims flux is lost at a rate of

$$\frac{d\phi}{dt} = -2sv_{\Delta}\mu_0 H \quad (2-6)$$

where

$s$  is a mean depth of ripples in the slipping surfaces

$v_{\Delta}$  is the detonation velocity shown in Figure 2-2

$\mu_0$  is the magnetic permeability

$H$  is the magnetic field

In a manner similar to that of Knoepfel, it has been determined that

$$\frac{I}{I_0} = (C(t))^{1 - \frac{2s}{d}} \quad (2-7)$$

where

$I_0$  is the initial current in the generator

$C(t)$  is the flux compression factor determined in Chapter III

$s$  is the mean depth of the ripples

$d$  is the initial plate separation

In this manner, an output current can be determined.

A second empirical method to account for additional losses adjusts the time varying inductance of the generator predicted by the resistance model. This additional inductance  $L_{ex}$  is added to the total time varying generator inductance.

$$L_{Gen}(t) = L_G(t) + L_{ex}(t) \quad (2-8)$$

where  $L_G(t)$  is the time varying inductance predicted by the Gurney method.  $L_{ex}(t)$  can be either negative or positive in value. A

negative value indicates a faster flux compression and smaller time varying inductance. A positive value indicates a slower flux compression and larger time varying inductance.

Finally, the generator's performance can be empirically modeled by calculating a flux trapping efficiency.

$$\text{Eff} = \frac{\text{Ideal Flux Present} - \text{Flux Lost} \times 100\%}{\text{Ideal Flux Present}} \quad (2-9)$$

The ideal flux present is the initial flux present when generator operation begins. The flux lost is all flux lost regardless of the loss mechanism.

### III. Computer Model

Five basic models were developed to described MCG operation. Two of these models, the flux conserved model and the time varying resistance model are theoretical equivalent circuit models. The remaining models, the sliding contact loss model, the changing area loss model, and the efficiency model are empirical models.

All models are derived from the flux conserved model. The models are capable of describing operation for both rectangular and trapezoidal geometry strip generators. A detailed description of the program inputs, outputs, and the program itself can be found in Appendix A.

#### Theoretical Models

Flux Conserved Model. The flux conserved model uses an equivalent electrical circuit approach to model the MCG's operation. This model assumes that there are no flux diffusion losses and that the metal plates are perfectly conducting so that the circuit has essentially no resistance. The circuit relationship is then

$$\frac{d}{dt}(LI) = 0 \quad (3-1)$$

The current solution at any time,  $t$ , is then given by

$$I(t) = I_0 \frac{L(0)}{L(t)} \quad (3-2)$$

where

$L(0)$  and  $I_0$  are initial conditions at  $t=0$

$L(t)$  is a time varying system inductance

With no losses, the MCG operation may be modeled completely by a time varying inductance. For this particular circuit, there are three inductances, the generator inductance,  $L_G$ , the load inductance,  $L_L$ , and the throat inductance,  $L_0$ . The throat inductance is the inductance of the small transmission line connecting the generator to the load. Both  $L_L$  and  $L_0$  are assumed to be constant.

The generator inductance varies with time. The change in inductance results from the conversion and partial transfer of chemical energy of the explosive to the kinetic energy of the top metal plate. Rather than using a complex computer code to derive this energy transfer, this computer model uses the Gurney method which provides a quick, accurate approximation of the energy transfer.

The Gurney method is based on energy and momentum balances and can be used to describe a large variety of geometries. For the strip generators, the top plate, explosive, and tamper can be modeled as an asymmetric sandwich as shown in Figure 3-1.

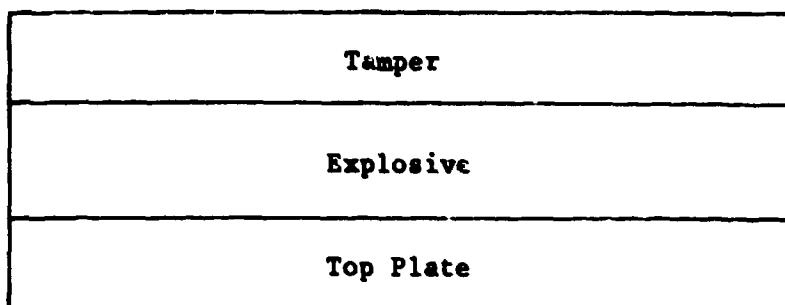


Figure 3-1. Asymmetric Sandwich

In this particular configuration, the velocity imparted to the metal is described as

$$v_m = \sqrt{2E} \left( \frac{1 + A^2}{3(1 + A)} + \frac{N}{C} A^2 + \frac{M}{C} \right)^{-1/2} \quad (3-3)$$

where

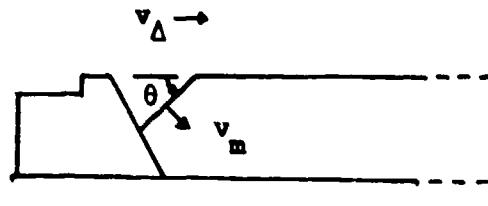
$\sqrt{2E}$  is the Gurney energy for the particular explosive

$\frac{N}{C}$  is the tamper mass to explosive mass ratio

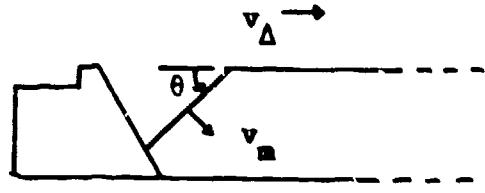
$\frac{M}{C}$  is the metal mass to explosive mass ratio

$A$  is a constant defined by  $\frac{1 + \frac{M}{C}}{1 + \frac{N}{C}}$  (6:8)

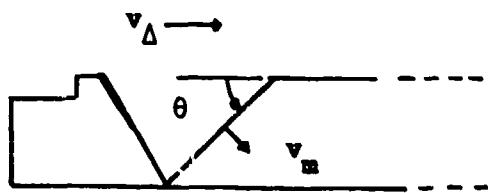
As the explosive burns, the top plate is driven to the bottom plate as shown in Figure 3-2.



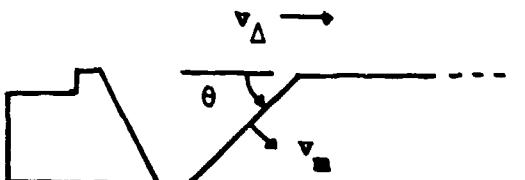
$t_1$



$t_2$



$t_3$



$t_4$

Figure 3-2. Compression of Generator

The angle,  $\Delta$ , shown in Figure 3-2 is known as the Gurney angle. The Gurney angle is defined by the following equation

$$\theta = \sin^{-1} \left( \frac{v_m}{2v_\Delta} \right) \quad (3-4)$$

where

$v_m$  is the metal velocity from Eq (3-3)

$v_\Delta$  is the detonation velocity of the explosive (6:27)

Using the detonation velocity, the Gurney angle, and simple geometry, a time varying area can easily be calculated. Generation operation ceases when the top plate of the generator touches the jet catcher as shown in Figure 3-3.

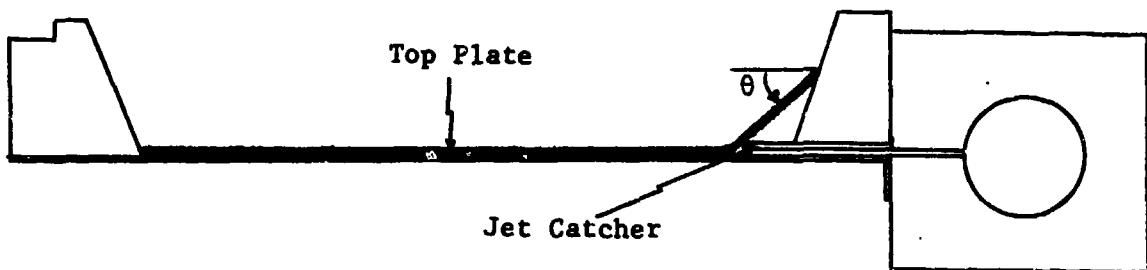


Figure 3-3. Generator Ceasation

Using this time varying area, the time varying inductance is easily calculated using

$$L(t) = \frac{1.2566371 A(t)}{W} \mu H \quad (3-5)$$

where

$A(t)$  is the time varying area in  $m^2$

$W$  is the plate width in  $m$

Because the program allows for the width of the plate to vary,  $L(t)$  is calculated incrementally.

Once the time varying generator inductance is calculated, the system inductance can be defined as

$$L(t) = L_G(t) + l_0 + L_L \quad (3-6)$$

The flux conserved solution to Eq (3-2) is then

$$I_{Ideal}(t) = I_0 \frac{L_G(0) + l_0 + L_L}{L_G(t) + l_0 + L_L} \quad (3-7)$$

From this ideal current the magnetic field and magnetic flux density are easily found using

$$H(t) = \frac{I_{Ideal}(t)}{W} \quad (3-8)$$

and

$$B(t) = \mu_0 H(t) \quad (3-9)$$

Time Varying Resistance Model. The time varying resistance model also uses an equivalent electrical circuit approach. It assumes the

only resistive mechanisms are flux diffusion and plate resistivity.

The circuit relationship is then

$$\frac{d}{dt}(LI) + IR = 0 \quad (3-10)$$

The current solution at any time is then

$$I(t) = I_0 \frac{L(0)}{L(t)} e^{-\int_0^t \frac{R(t)}{L(t)} dt} \quad (3-11)$$

where

$L(0)$  and  $I_0$  are initial conditions at  $t=0$

$L(t)$  is the time varying system inductance

$R(t)$  is the time varying system resistance

$L(t)$  has been described in the flux conserved model and the mechanism for its generation is identical in the time varying resistance model. In this particular model, it is assumed that all resistive mechanisms are described by the resistivity of the copper plates or as an equivalent resistance due to flux diffusion.

Plate resistance is described by the well-known relationship

$$R_p = \frac{\rho l}{A} \quad (3-12)$$

where

$\rho$  is resistivity

$l$  is path length

$A$  is cross sectional area in which the current flows

As metal heats, its resistivity changes. As long as the plates remain solid, this change can be approximated by the linear function

$$\rho = \rho_0(1 + k\theta) \quad (3-13)$$

where

- $\rho_0$  is resistivity at room temperature
- $k$  is a proportionality constant ( $\sim 10^{-3}/^{\circ}\text{C}$ )
- $\theta$  is the temperature in  $^{\circ}\text{C}$  (10:393)

A method must then be used for describing how the temperature changes with time. A reasonable approximation for temperature below melting point is

$$\theta = \chi B^2 \quad (3-14)$$

where

- $\chi = 1170^{\circ}\text{C}/(\text{MG})^2$
- $B$  is the magnetic flux density in megagauss (10:392)
- $\chi$  is a function of the specific heat,  $C_p$ , and the magnetic permeability,  $\mu_0$ . Resistivity can then be described as

$$\rho(t) = \rho_0(1 + k\chi B^2) \quad (3-15)$$

The path length also varies with time. As the generator is compressed, the path length decreases. By using simple geometry and the Gurney angle, a time varying path length is calculated. The cross sectional area of the plate is defined as

$$A = Wd \quad (3-16)$$

where

- $W$  is the width of the generator
- $d$  is the depth of penetration of the magnetic field

$d$  is defined as

$$d = 2\sqrt{\kappa_0 t} \quad (3-17)$$

where

$$\kappa_0 = \frac{\rho}{\mu} \text{ and } \rho \text{ is defined in Eq (3-13)}$$

$t$  is time

Coupling all these time varying functions together results in a piece wise continuous time varying  $R_p(t)$ .

During generator operation, a portion of the flux diffuses into the conductor. By using the skin layer method described in Knoepfel (1:184-186), the flux resistance could be modeled as a time varying resistance by

$$R_d = \frac{\rho}{s_\psi} \quad (3-18)$$

where

$\rho$  is the resistivity described by Eq (3-13)

$s_\psi$  is a magnetic skin depth

$s_\psi$  is defined as

$$s_\psi = \sqrt{\kappa_0 \tau} \quad (3-19)$$

where

$$\kappa_0 = \frac{\rho}{\mu}$$

$$\tau = \frac{H}{\frac{dH}{dt}} \text{ based on the ideal magnetic fields}$$

Coupling these time varying functions together results in a time varying  $R_d(t)$ . The total system time varying resistance is then described by

$$R(t) = R_p(t) + R_d(t) \quad (3-20)$$

The resistance model solution to Eq (3-10) is then

$$I_{Res}(t) = \left\{ \frac{L_G(0) + L_0 + L_L}{L_G(t) + L_0 + L_L} \right\} I_0 \exp \left[ - \int_0^t \frac{R_p(t) + R_d(t)}{L_G(t) + L_0 + L_L} dt \right] \quad (3-21)$$

Integration is done using the trapezoidal approximation. The magnetic fields are found in a manner identical to that of the ideal case substituting  $I_{Res}$  for  $I_{Ideal}$ .

#### Empirical Models

Empirical models were developed when it was discovered that the resistive loss mechanisms were not the primary loss mechanism. Each of the following models uses a different approach to attempt to model the additional loss mechanisms occurring in the generator.

Sliding Contact Model. In a manner similar to that of Knoepfel (1:189-191), an empirical model for slipping contact losses was developed. Knoepfel accounts for all losses with his sliding contact loss. The sliding contact model developed herein assumes the loss mechanisms are resistive losses and sliding contact losses. The sliding contact loss mechanism is due to flux trapping when two plates are driven together and the plate surfaces do not come together smoothly.

It was assumed that the sliding contact current could be described by

$$I_{\text{Slip}}(t) = I_0 \left[ \frac{I_{\text{Res}}(t)}{I_0} \right] 1 - \frac{2s}{d} \quad (3-22)$$

where

$I_0$  is the initial current

$I_{\text{Res}}(t)$  is the time varying current using the resistive model

$s$  is a mean ripple depth

$d$  is the initial plate separation

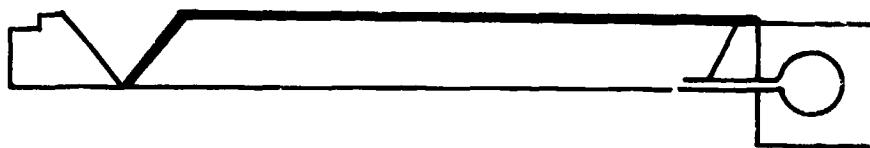
Solving Eq (3-21) for  $s$  yields

$$s = \frac{d}{2} \left( \log \frac{I_{\text{Res}}(t)}{I_0} - \log \frac{I_{\text{Slip}}(t)}{I_0} + 1 \right) \quad (3-23)$$

Using experimental data,  $s(t)$  was calculated for each test using the actual current in place of  $I_{\text{Slip}}(t)$ . These curves were linearized using three times during generator operation. These times are shown in Figure 3-4. The first match point corresponds to when the top plate has completed its run down the cutting wedge and begins to compress against the bottom plate. The second match point corresponds to when the top plate of the generator is about to begin its run down the end wedge. The final match point occurs when the maximum experimental output current is reached.

The ripple depth at each match point is calculated from Eq (3-23), and the ripple depth at any point between the match points is found through linear interpolation. From the sets of data, best and worst case slipping losses were modeled.  $I_{\text{Slip}}(t)$  is then calculated using Eq (3-21) and the experimentally derived, computer linearized ripple

depth,  $s(t)$ . The magnetic fields are again found in a manner identical to that of the ideal case substituting  $I_{\text{Ideal}}$  with  $I_{\text{Slip}}$ .



Point 1



Point 2



Point 3

Figure 3-4. Slipping Model Match Points

Changing Area Loss Model. Since the ripple depth,  $s$ , could not be tied to any known parameter, a changing area loss model was developed. This model assumes that the changing inductance derived from the

Gurney approximations may be incorrect. It assumes that the generator inductance can be defined as

$$L_{\text{Gen}}(t) = L_G(t) + L_{\text{ex}}(t) \quad (3-24)$$

where

$L_G(t)$  is the generator inductance calculated from the Gurney approximations

$L_{\text{ex}}(t)$  is an additional inductance caused by incomplete Gurney compression

If we replace  $L_G(t)$  in Eq (3-21) with  $L_{\text{Gen}}(t)$ , the principal effect is to decrease the flux compression factor,  $\gamma(t)$ .

$$\gamma(t) = \frac{L_G(0) + L_0 + L_L}{L_{\text{Gen}}(t) + L_0 + L_L} \quad (3-25)$$

Because  $L_G(t)$  is determined by a changing area, so too is  $L_{\text{Gen}}(t)$ .

This model assumes that the changing area current can be described by

$$I_{\text{Carea}}(t) = I_0 \frac{L_G(0) + L_0 + L_L}{L_G(t) + L_{\text{ex}}(t) + L_0 + L_L} \exp \left[ - \int_0^t \frac{R_d(t) + R_p(t)}{L_{\text{Gen}} + L_0 + L_L} dt \right] \quad (3-26)$$

Solving Eq (3-26) for  $L_{\text{ex}}(t)$  yields

$$L_{\text{ex}}(t) = I_0 \frac{L_G(0) + L_0 + L_L}{I_{\text{Carea}}(t)} \exp \left[ - \int_0^t \frac{R}{L} dt - (L_G(t) + L_0 + L_L) \right] \quad (3-27)$$

Using experimental data,  $L_{ex}(t)$  was calculated for each test using the actual current in place of  $I_{Carea}(t)$ . Once calculated, a changing area was calculated using Eq (3-5).

$$A_{ex}(t) = \frac{L_{ex}(t)W}{\mu_0} \quad (3-28)$$

This changing area was then graphed for analysis.

Efficiency Model. In a manner similar to that of Fowler, a flux trapping efficiency model was developed (12:26). Using the well-known relationship for flux of

$$\phi = LI \quad (3-29)$$

a time varying  $\phi$  was developed. In this model, it is assumed that  $L_G(t)$  from the Gurney calculations is a valid representation of the time varying inductance. This model makes no attempt to physically explain where or why the flux loss occurs. It models all losses, whether due to slipping or due to inaccuracies in the Gurney derived inductance as a time varying flux trapping efficiency. This flux trapping efficiency is defined by

$$\epsilon = \frac{\phi_0 - \phi(t)}{\phi_0} \quad (3-30)$$

where

$\phi_0$  is the initial flux in the system

$\phi(t)$  is calculated from test data

This efficiency is smoothed out and linearized and a best and worst case efficiencies are determined. An efficiency current is then determined using

$$I_{\text{Eff}}(t) = cI_{\text{Res}}(t) \quad (3-31)$$

The magnetic fields are found in a manner identical to that of the ideal case substituting  $I_{\text{Ideal}}$  with  $I_{\text{Eff}}$ .

#### IV. Experimental Apparatus

Experiments to validate the computer model were conducted at the Air Force Weapons Laboratory explosive test facility located on the McCormick Range at Kirtland AFB, New Mexico. The major components and diagnostic equipment used in the magnetocumulative generator tests are described in detail in this chapter. The major components consist of the capacitor bank, the solid dielectric explosive closing switch, the fire control system, the transmission line, and the MCG and load coil (See Figure 4-1). The primary diagnostic devices used in the experiments were Rogowski coils, voltage probes, and oscilloscopes.

##### Major Components

Capacitor Bank. The capacitor bank provided the initial feed current to the MCG. The bank consisted of fifty 6.1  $\mu$ F 60 KV capacitors connected in parallel to yield a total nominal capacitance of 305  $\mu$ F. Charge voltages between 15 KV and 45 KV were used. The bank was charged by a Maxwell Laboratory charging system and discharged into the transmission line and MCG through a solid dielectric closing switch.

Closing Switch. The closing switch used during the experiments was a solid dielectric explosive switch. The switch consisted of two 6 foot long by 8 inch wide by 0.5 inch thick steel plates. The connection of the closing switch to the transmission line and capacitor bank is shown in Figure 4-1.

One of the plates was connected via the solid inner conductors of numerous parallel coaxial cables to the capacitor bank. The other

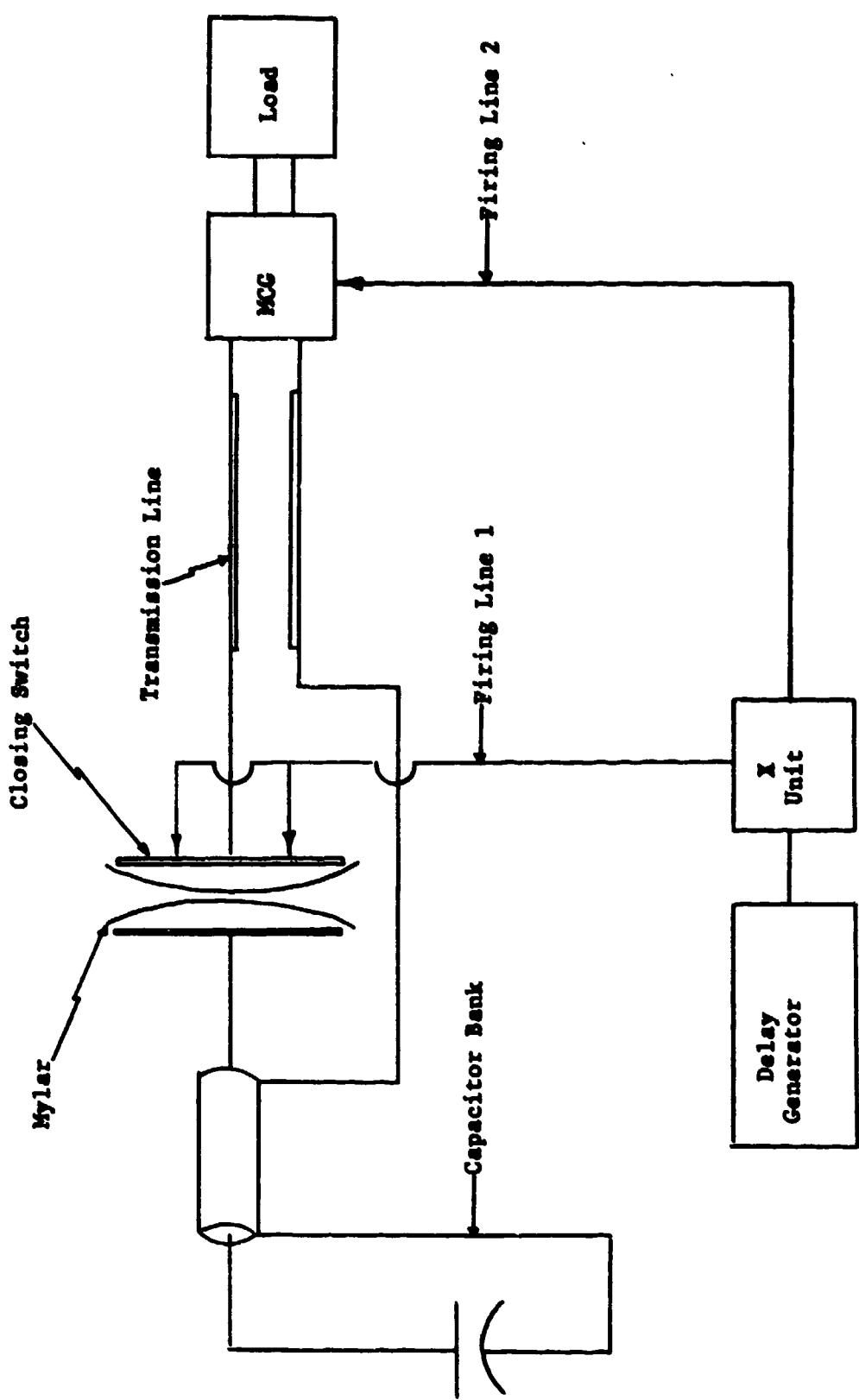


Figure 4-1. MCC Experimental Set Up

plate was attached to the top of the transmission line and could be pulled back to facilitate cleaning and rebuilding of the switch.

Sheets of mylar sandwiched between the two aligned plates acted as the solid dielectric insulation for the switch. A 1 mil thickness of mylar was used for each 1 KV of potential across the plates. Plate separation was determined by the number of sheets of mylar required for the test voltage applied.

Before each test, two RP2 PETN explosive shaped charge detonators were placed into 0.5 inch holes which were drilled along the top edge of the plate connected to the transmission line. Closing of the switch occurred when the two detonators were fired, rupturing the mylar insulation and allowing breakdown of the switch. The capacitor bank then discharged its energy through the switch into the transmission line and the MCG.

Because of its destructive nature, the switch required rebuilding after each shot. Rebuilding consisted of replacing the mylar sheets between the plates, replacing the detonators, and reconnecting the detonation lines to the X Units.

Firing System. The firing systems consisted of two TRW Model 64A Trigger Delay Generators and a Los Alamos National Laboratory X Unit. The trigger delay generators provided a variable time delayed output pulse to fire the X Unit and trigger the other diagnostic equipment. The X Unit provided the current pulse used to fire the detonators in both the switch bunker and the explosive on the MCG.

Transmission Line. The transmission line consisted of two parallel plates of 60 mil aluminum, 40 feet long and 4 feet wide.

This length allowed the feed current to be delivered to the MCG at a safe distance from the bunker and switch, avoiding damage to the switch during the MCG explosions.

The two aluminum sheets are separated by twelve sheets of 5 mil thick 6 foot wide mylar. This allows for a hold off voltage of 60 KV at 1 mil per kilovolt. The total insulation thickness of 60 mils results in a line capacitance of

$$\begin{aligned} C &= \epsilon A/d \\ &= 0.26 \mu\text{F} \end{aligned} \tag{4-1}$$

Since  $C_{\text{Line}} \ll C_{\text{Bank}}$ ,  $C_{\text{Line}}$  was neglected in all circuit calculations. The plate edges were further insulated against edge field enhancement effects by the placement of 0.5 inch diameter tygon tubing between the sixth and seventh sheets of mylar along the edge of the entire length of the line (3).

Because the end of the transmission line was connected directly to the MCG, it was destroyed with each test. To avoid replacing the entire transmission line, 6 foot long by 4 foot wide end pieces were bolted onto the end of the line using clamping bars to ensure good electrical contact. Sandbags protected the clamping bars during the explosions. Following each test, the end pieces and final sections of mylar were replaced.

#### Diagnostics

Rogowski Coils. Rogowski coils provide a means to measure the derivative of time varying high currents, responding only to the current passing through the coil loop (13:180).

Four Rogowski coils were used for each test, placed as shown in Figure 4-2.

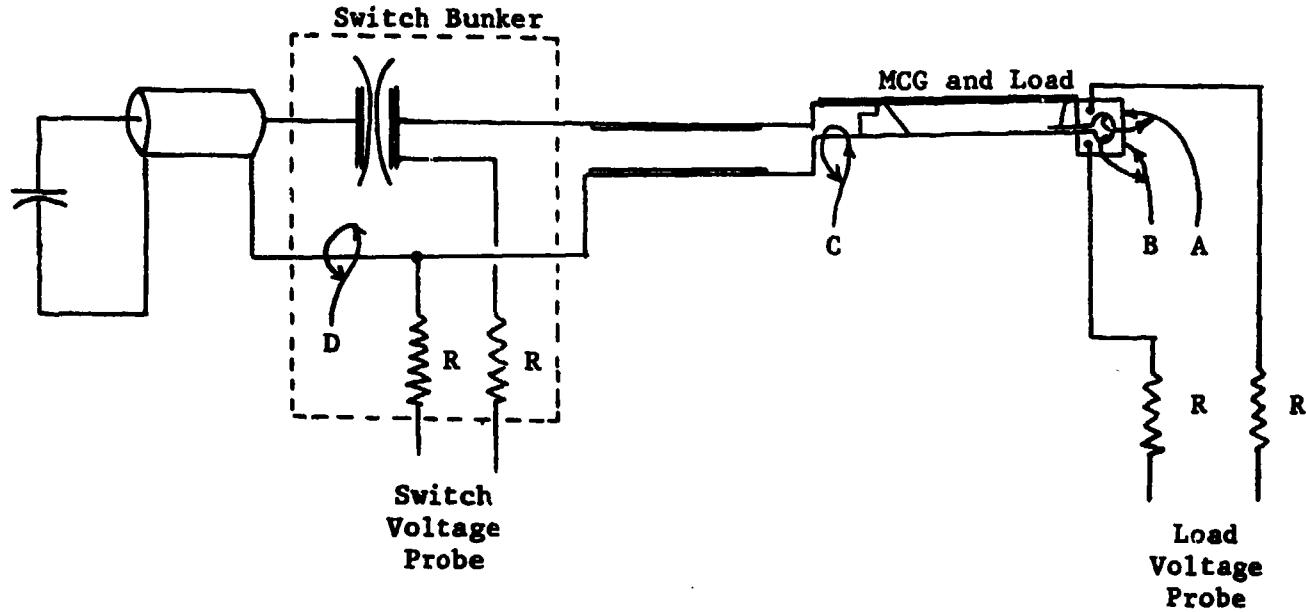


Figure 4-2. Placement of Test Diagnostic Devices

Coils A and B were used to measure the load current derivative. Coil C was used to measure the feed current derivative until crowbarring occurs and Coil D, located in the switch bunker, measured the derivative of the return current of the transmission line.

Both handwound and etched Rogowski coils were used. The handwound Rogowski coils provided a 1 volt signal for every  $10^9$  A/sec present while the etched Rogowski coils provided a 1 volt signal for every  $10^{10}$  A/sec present. Coil A was etched, while coils B, C, and D were handwound.

To enhance coil survivability during the explosion, all four Rogowski coils were placed inside through tygon tubing. Coils A, B, and C were destroyed during each test and had to be replaced prior to the next shot. Coil D remained undamaged throughout the explosion and thus provided a uniform means to compare the input parameters from test to test.

The current derivatives from coils A, B, and D were actively integrated using Textronixs Type 0 Operational Amplifier integrators. The output from these integrators was fed into oscilloscopes and recorded on film.

Voltage Probes. At least one voltage probe was used in each experiment; the one located in the switch bunker was used to measure the voltage across the switch. In the experiments where a MCG load coil of 10.31 nH was used, a second voltage probe was connected to the load coil to measure the voltage across the load during the operation of the MCG. The voltage probes consisted of resistive dividers to measure voltage and were connected as shown in Figure 4-2. In both voltage probes, the two resistors were filled with a copper sulfate solution with copper electrodes sealing each end. The copper sulfate solution was adjusted to give a nominal resistance of 20 K $\Omega$ . Coaxial diagnostic cables fed the signals to 50  $\Omega$  terminators across the oscilloscope inputs. Therefore, a 2.5 volt signal was measured at the oscilloscope for every 1 KV across the switch or load coil. The outer cable shields were shorted together at the resistors and at the oscilloscope inputs to balance any induced shield currents. The two signals from each probe were then connected to a differential amplifier which eliminated any common mode signals (13:182).

Oscilloscopes. Data from each test was recorded on fourteen Textronixs 7603 oscilloscopes. Four oscilloscopes recorded signals generated from each load Rogowski coil with two recording  $dI/dt$  and two recording the integrated current waveforms. Two oscilloscopes measured the differential voltage across the load when the 10.31 nH load was used. One oscilloscope was used to record the line  $dI/dt$  from coil C. Another oscilloscope recorded the line  $dI/dt$  from coil D. Two other oscilloscopes recorded the integrated current from coil D and the differential voltage across the switch. The data from each of the oscilloscopes was recorded by Polaroid cameras which were triggered by the delay generators.

## V. Experimental Procedures

Five strip geometry magnetocumulative generator experiments, referred to as MCG shots, were performed in order to obtain data with which the computer model could be compared and validated. Prior to every MCG shot, two preliminary experiments were conducted. The first of these, referred to as a line short shot was required to obtain element values for the equivalent circuit of the capacitor bank and transmission line. The second, referred to as a MCG short shot, was conducted in order to calibrate the diagnostic Rogowski coils which would be used during the actual MCG shot. This chapter describes in detail the general procedures that are common to all three of these shots. It then describes the experimental procedures which are unique to the line short shot, the MCG short shot, and the MCG shot.

### General Procedures

Prior to each shot several experimental procedures common to all shots were performed. These procedures include diagnostic line tests, X Unit and detonation line tests, and preparation of the oscilloscopes.

Diagnostic Line Tests. To preclude the loss of experimental data due to faulty diagnostic lines, these lines were tested prior to each shot. A repetitive train of pulses from the TRW Delay Generators was delivered to the MCG connection end of the transmission line via a test line. This test signal was connected to each diagnostic line in turn. The return signal was then monitored on an oscilloscope to insure that the line was operating reliably prior to being connected to a Rogowski coil or voltage probe.

X Unit and Detonation Line Test. Prior to each test, the X Units and detonation lines were tested for reliable operation and timing. Blown bridge wires were attached to the detonation lines to simulate detonators during the test. Using a pencil, a carbon path was marked between the two terminals where the bridge wire was originally connected, providing a path for breakdown when the X Units fired. The resulting flash and distinctive pop accompanying this breakdown gave clear indication that the X Units were operating correctly.

Preparation of the Oscilloscopes. Preparation of the oscilloscopes prior to each shot included calibration, setting of graticules, and setting of baselines. Once the scopes were calibrated, the graticules and baselines were adjusted to levels which would ensure clear data recording of measured signals with cameras.

Just prior to the shot, the shutters of the Polaroid cameras were opened to record the graticules. The graticules were then turned off to prevent them from being recorded again during the shot. As the capacitor bank was being charged, the shutters were opened one final time in order to record the data signals. The TRW Delay Generators were coordinated with the data signals from the various Rogowski coils and voltage probes.

#### Line Short Shots

A total of four line short shots were performed to determine circuit element values for the equivalent circuit model of the capacitor bank, switch, transmission line, and connections. This section describes the line short shot and the general procedures to obtain these circuit element values.

For line short shots the ends of the transmission line where the MCG would later be connected were shorted together giving rise to the name line short shot. The two load Rogowski coils and the end of the line current Rogowski coil were looped around the shorting bar at the end of the line.

The capacitor bank was charged and then discharged through the switch and the transmission line. This resulted in an exponentially damped sinusoidal waveform (See Figure 5-1).

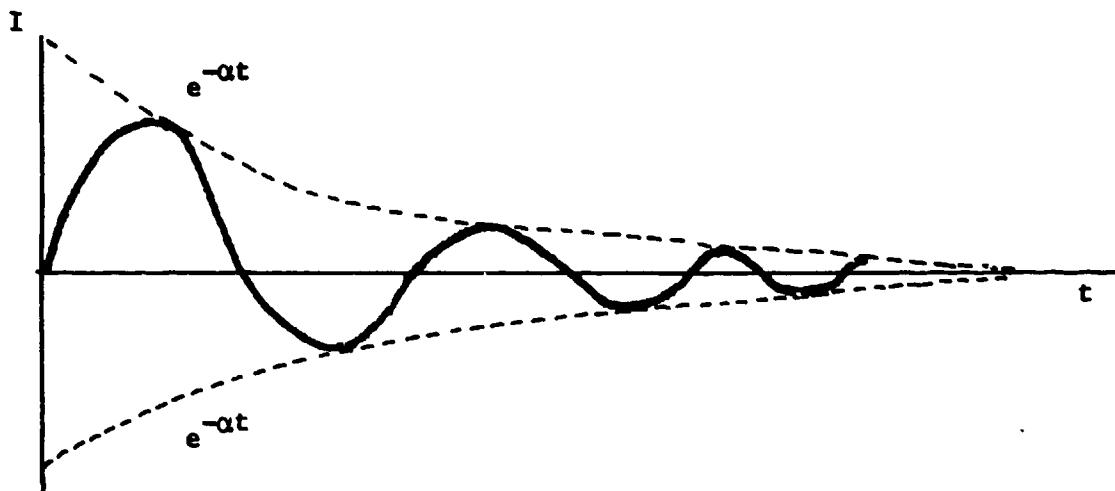


Figure 5-1. Typical Short Circuit Plot

The only known values in these experiments were the bank capacitance,  $C_{Bank}$ , and the charge voltage,  $V_0$ . All other capacitances were neglected because they were much less than  $C_{Bank}$ . The period,  $\tau$ , was determined directly from the oscilloscope traces.

The solution to a time invariant RLC circuit is well-known (1:132). A least squares fit was done to determine the exponential damping factor,  $\alpha$ , shown in Figure 5-1. Knowing  $\tau$ ,  $C$ , and  $\alpha$ , the circuit inductance was calculated using

$$\begin{aligned}\tau &= 2\pi\omega_r \\ &= 2\pi/\{(\omega_0)^2 - (\alpha)^2\}^{1/2}\end{aligned}\quad (5-1)$$

where  $\omega_0 = \frac{1}{\sqrt{LC}}$

yielding

$$L = \tau^2/C(4\pi^2 + \tau\alpha^2) \quad (5-2)$$

and the circuit resistance was determined by

$$R = 2\alpha L \quad (5-3)$$

In MCG work, the input circuit is crowbarred away from the generator after the first quarter cycle at  $I_{\text{Peak}}$ . A comparison of the values of  $I_{\text{Peak}}$  and the quarter cycle time using the time invariant RLC solution and an approximate LC solution showed that  $R$  could be neglected without significant loss of accuracy.

#### MCG Short Shots

This section describes in detail the MCG short shot and the general procedures for calculating the total system inductance and the sensitivities of the Rogowski coils. A minimum of one MCG short shot was performed prior to each MCG shot. For a successful MCG shot, the entire system must operate reliably. When one part of the system was found to have a problem, it was fixed or replaced and another MCG

short test was performed. For this reason, as many as four MCG short shots were performed prior to one actual MCG shot. These shots provide a final test of the entire system to ensure all components were operating correctly.

These shots provided oscilloscope traces of the current outputs from which the total system inductance would be determined. They also provided  $dI/dt$  traces from each Rogowski coil so that their sensitivities could be experimentally determined prior to the actual MCG shot..

For the MCG short shot, the MCG was bolted to the end of the transmission line in the same manner as for the actual shot. The only differences were the lack of explosive on the generator and the placement of the load voltage probe. The two load coil Rogowski coils were placed through the load coil and the end of the line return Rogowski coil was placed around the bottom return transmission line's plate at the connection to the MCG. For the actual MCG shot, these were moved to the load coil.

The capacitor bank was charged to 1.5 KV for each MCG short shot. The capacitor bank was then discharged through the switch, transmission line, and the MCG. This again resulted in a damped sinusoidal waveform.

The oscilloscope traces from the MCG short shot were used in order to determine the total system inductance of the capacitor bank, the switch, the transmission line, connections, and the MCG. The period,  $\tau$ , of the damped sinusoidal waveform was read directly from the traces.

With a known bank capacitance and neglecting system resistance, the total system inductance could be determined using

$$\tau = 2\pi\sqrt{L_T C_{\text{Bank}}} \quad (5-4)$$

which when solved for the inductance yields

$$L_T = \tau^2 / 4\pi^2 C_{Bank} \quad (5-5)$$

Oscilloscope traces of  $dI/dt$  from each Rogowski coils were used to experimentally determine the sensitivity of the Rogowski coils which would be used during the succeeding MCG shot. Knowing the capacitor bank charge voltage,  $V_0$ , the total inductance,  $L_T$ , and neglecting system resistance, the maximum  $dI/dt$  is given by

$$\frac{dI}{dt}_{max} = \frac{V_0}{L_T} \quad (5-6)$$

Measuring the maximum voltage of the  $dI/dt$  trace, the sensitivity of the Rogowski coil is given by

$$\text{Sensitivity} = \frac{dI}{dt}_{max} / V_{max} \quad (5-7)$$

With the integrator time constant,  $TI$ , the sensitivity of the Rogowski coil and the voltage peak of the integrated  $dI/dt$  trace,  $V_p$ ,  $I_{Peak}$  was calculated using

$$I_{Peak} = V_p \times \text{Sensitivity} \times TI \quad (5-8)$$

This  $I_{Peak}$  was then compared with the value predicted by the time invariant RLC solution as a check of the integrators. This procedure was performed for each coil to be used during the actual MCG shot.

#### MCG Shots

A total of five MCG shots were performed to obtain data for validation of the computer model. This section details the set up, procedures, and input conditions for each of these shots.

The explosive used in all shots was DuPont Detashet. As described earlier in this chapter, the total system inductance as well as the sensitivities of the Rogowski coils were determined during a MCG short shot just prior to the actual MCG shot. The total inductance varies with the length of the transmission line end pieces and the connection to the MCG. After the MCG short shot, the X Units and detonation lines were once again tested, the switch rebuilt, and the oscilloscopes prepared. During this period of time explosives are readied on the MCG by contractor personnel from the Civil Engineering Research Facility (CERF). Each generator is identical except for the size of the load coil. For three shots the load coil had an inductance of 10.31 nH. For two shots, a smaller load was used; one had an inductance of 0.2213 nH and the other had an inductance of 0.5701 nH. The MCG was placed on a plate of one inch steel which was separated from the MCG by several sheets of mylar. This steel plate is placed on a bed of cinder blocks. A smaller 40 inch long by 8 inch wide by 3/16 inch thick steel tamper is placed on top of the explosive for every shot. The amount of cement tamper placed on this steel sheet, as well as, the bank voltage varied from shot to shot. Shown in Table 5-1 is a summary of the input conditions for the five MCG shots.

Table 5-1  
Summary of Input Conditions

Test	V(KA)	L (nH)	I (KA)	Explosive Weight (lbs)	Steel Weight (lbs)	Cement Weight (lbs)	L Load (nH)
1	44.88	499.500	1100.00	1.85	4.911	5.0	10.31
2	25.00	437.700	294.00	8.16	4.911	20.0	10.31
3	25.40	487.693	630.00	5.90	4.911	10.0	10.31
4	27.70	540.380	652.00	7.37	4.911	20.0	0.5701
5	24.99	487.690	620.00	6.40	4.911	15.0	0.2213

## VI. Results and Conclusions

This chapter presents the results of the computer models and compares them with the experimental data. In addition, it includes recommendations for further study.

### Results

The goal of this study was to develop a computer model of the strip geometry MCG and to validate it through actual MCG shots. The primary criterion for evaluating the computer model was the model's ability to reproduce the current curves produced by actual MCG experiments. Accurate reproduction of these curves indicates that the computer program should be able to reliably predict the current curves for future tests. This section shows the results of the actual MCG shots and compares them with the results of the computer models.

A total of six experiments were conducted using the AFWL strip MCG. Five of these experiments were successful. The unsuccessful experiment was caused by a destructive failure of one of the capacitors in the capacitor bank. The results of the five successful shots are summarized in Table 6-1.

A plot of the actual current from the first experiment is shown in Figure 6-1. Actual currents from the remaining tests are contained in Appendix B. In four of the tests, crowbar occurred at or near  $I_{Peak}$  of the sinusoidal input current where  $dI/dt$  is equal to zero. In the second test, the generator crowbarred late resulting in an input current of 294.0 KA. Input currents varied from 294.0 to 1100.0 KA while output current peaks varied from 2210.0 to 10261.0 KA.

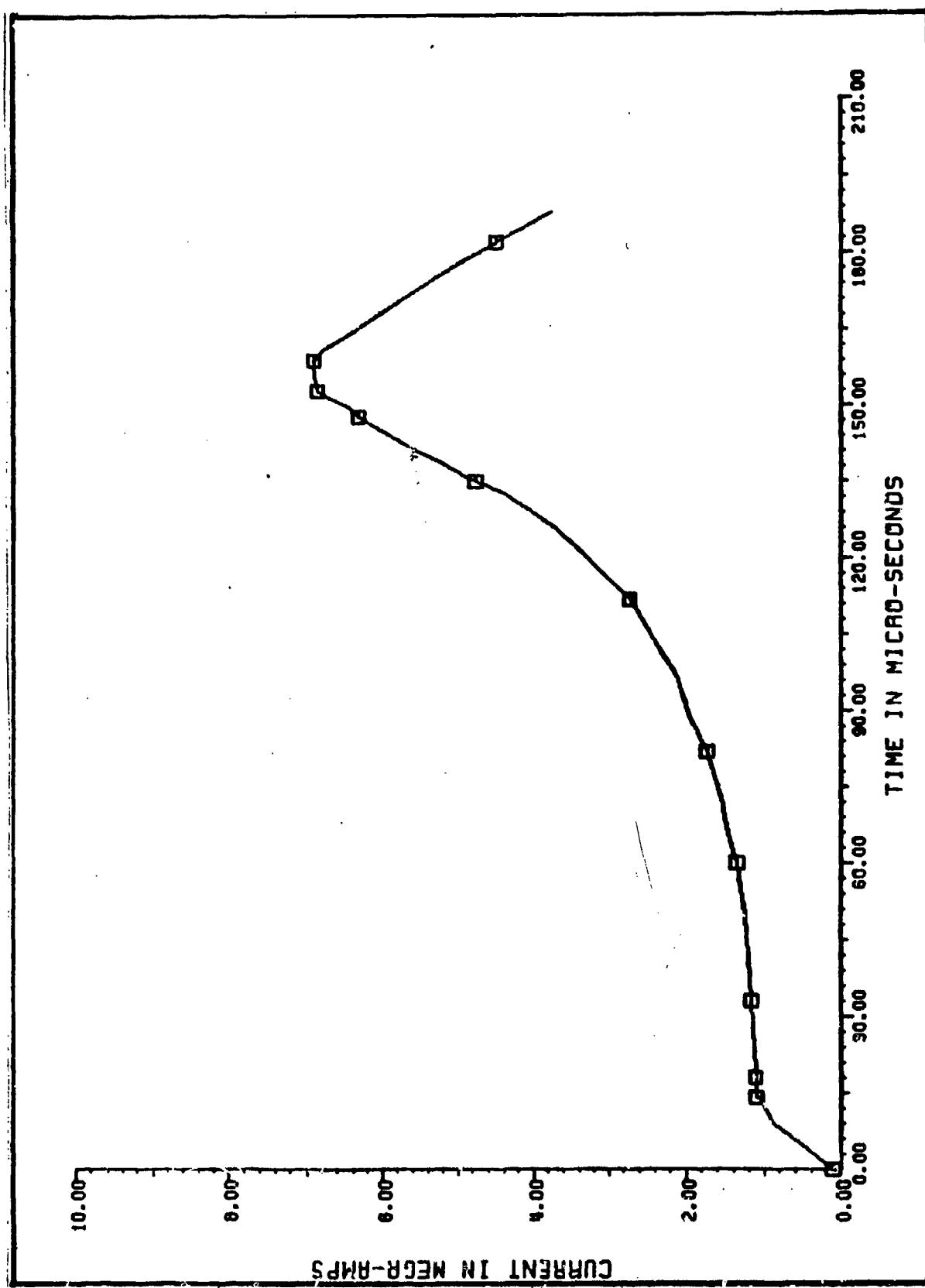


Figure 6-1. Experimental Current Test 1

Table 6-1  
Summary of Results

Test	Input Current (KA)	Maximum Output Current (KA) Ideal/Actual	Current Amplification Factor Ideal/Actual
1	1100.00	15188.6/6928.0	13.81/6.29
2	294.0	4128.7/2210.0	14.04/7.50
3	630.78	8715.3/5355.0	13.82/8.50
4	652.66	35646.0/10261.0	54.62/15.75
5	620.05	29556.4/6031.0	47.68/9.73

Computer Model Results. Based on the input parameters the computer program calculates and prints the currents predicted by each of five models: the flux conserved model, the resistance model, the sliding contact loss model, the changing area model, and the efficiency model. The results of these models are best described in terms of how well they correspond to the actual experimental data. The results are considered individually.

Flux Conserved Model. The flux conserved model calculates the output current as if no losses occur. The current is a function of only the time varying inductance, which in turn is a function of the detonation velocity and the Gurney angle. The time varying inductance which corresponds to a Gurney angle of  $5.6^{\circ}$  from the first test is shown in Figure 6.2

The flux conserved current versus the test current for the first test is shown in Figure 6-3; the curves for the remaining tests are shown in Appendix B. Points 1, 2, and 3 from Figure 3-4, corresponding

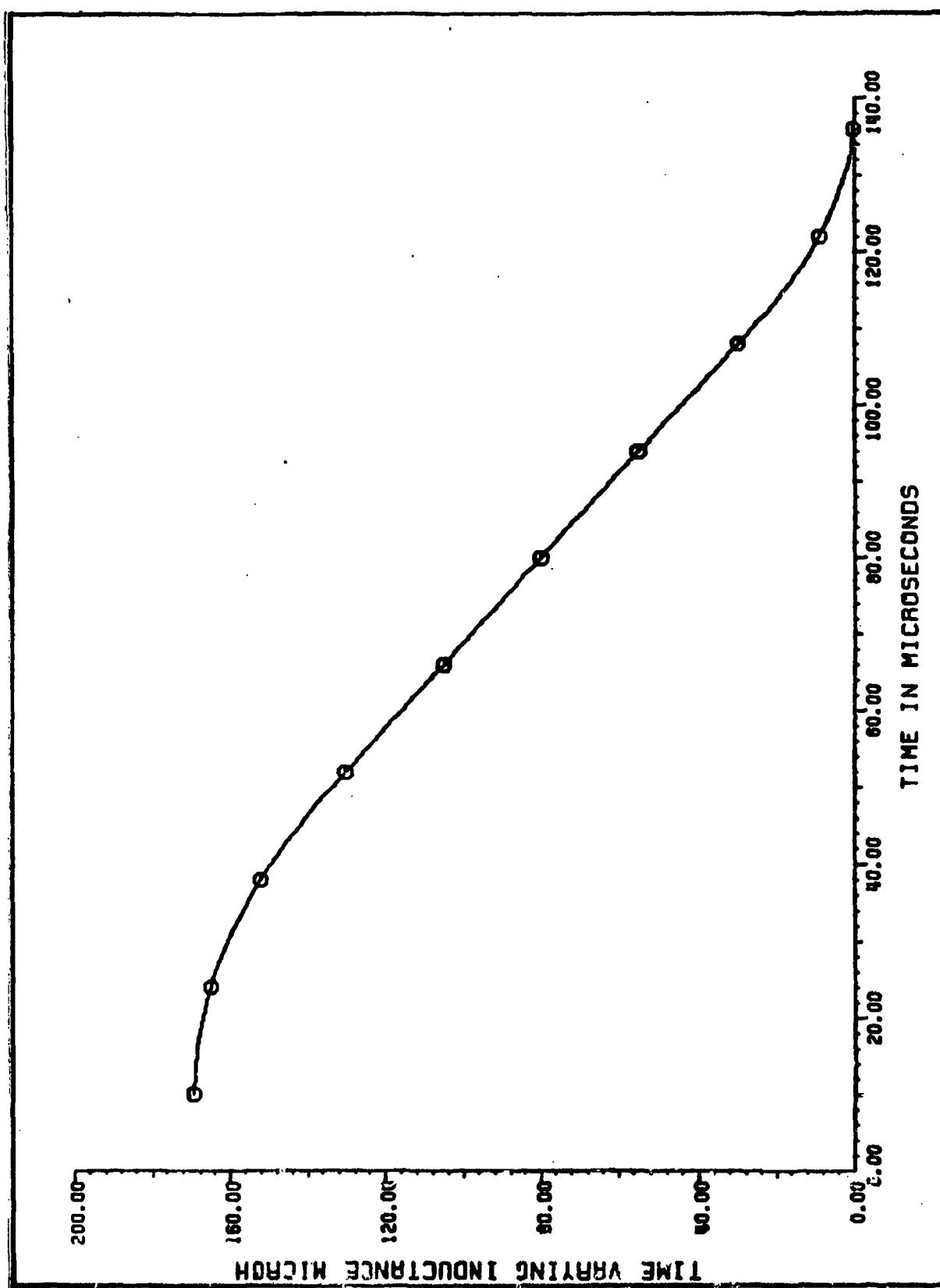


Figure 6-2. Time Varying Inductance

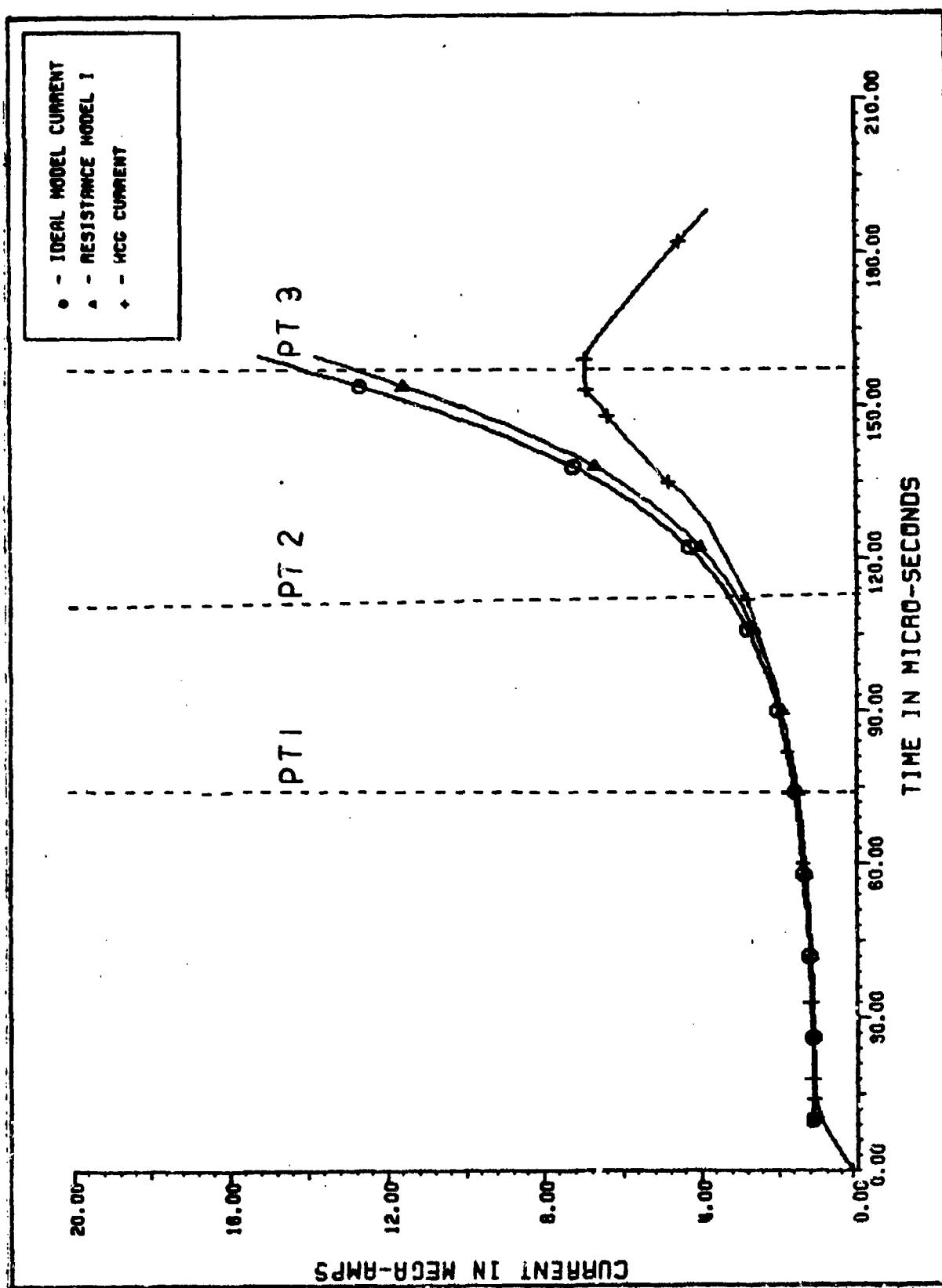


Figure 6-3. Equivalent Circuit Currents Test 1

to key generator operation points, are shown in this figure. A comparison of these two curves show that the flux conserved model provides a good approximation of the actual currents for the first 50% of generation. Because the flux conserved model neglects all losses, these plots show that for the first 50% of operation, the system is basically lossless. During the last 50% of operation this model predicts higher currents than those actually present. This indicates the presence of loss mechanisms which must be accounted for to obtain a complete model of the generator.

Resistance Model. The resistance model theoretically calculates the losses due to the plate resistance and flux diffusion equivalent resistance. A plot of the time varying resistance for the first test is shown in Figure 6-4; curves for the other tests are shown in Appendix B. A plot of the time varying resistance model's current versus the test current for the first test is shown in Figure 6-3.

These plots clearly indicate that plate resistance and flux diffusion resistance play only a limited role as loss mechanisms. Resistance effects are negligible during the initial 50% of generator operation, again indicating the system is essentially lossless during this time period. During the final 50% of operation, the time varying resistance predicts a current about 1% lower than that calculated by the flux conserved model.

An examination of the resistance shows that the plate resistances exceed the flux diffusion equivalent resistances by two orders of magnitude throughout generator operation. This indicates that flux diffusion plays only a minor role as a loss mechanism.

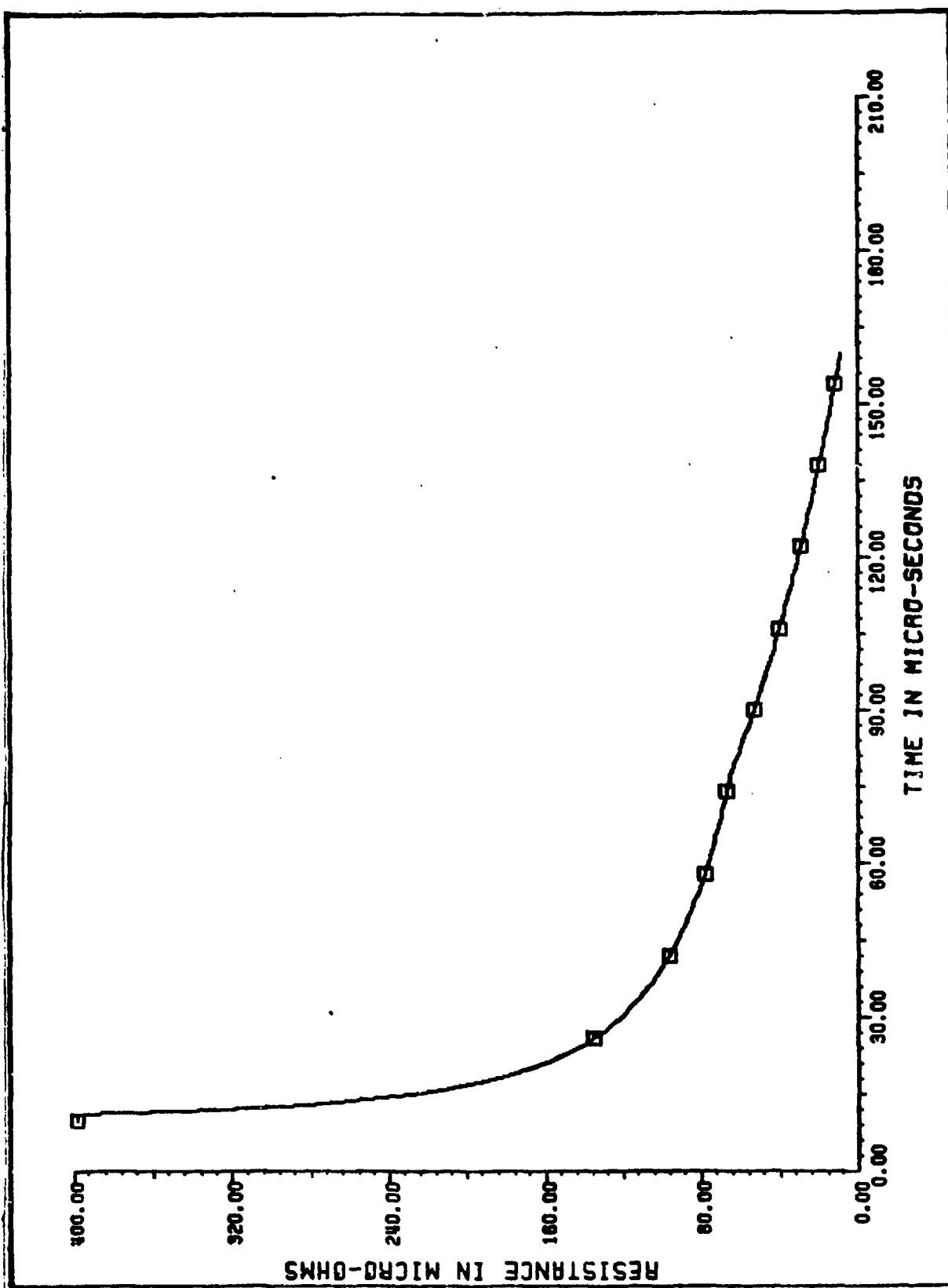


Figure 6-4. Time Varying Resistance Test 1

The resistivity which would be required were resistance alone to account for all losses in the generator's operation was calculated. This resistivity was found to be at least two orders of magnitude larger than the resistivity of vaporized copper. Since the magnitude of the ideal B fields was not sufficient to cause surface vaporization, a resistance this large was not reasonable. The resistance model's poor prediction during the final 50% of the generator's operation shows that additional loss mechanisms must be considered.

Sliding Contact Model. Unlike the flux conserved and resistance models, the sliding contact model is based on empirical data. A time varying mean ripple depth,  $s$ , was determined for the first three experiments with a load inductance of 10.31 nH. A plot of the  $s$  curve for the first experiment is shown in Figure 6-5, while the  $s$  curves for the second and third tests are presented in Appendix B. Points 1, 2, and 3 from Figure 3-4, corresponding to key generator operation points, are shown in this figure.

The bubble height gives a measure of how much flux is lost due to the sliding losses. Since  $s$  could not be linked to any parameter, a best and worst case sliding contact loss model was developed. Plots of the slipping loss model's best and worst case currents versus the test current for the first test are shown in Figure 6-6 with plots for later tests in Appendix B.

A comparison of these curves shows that the ranges described by the curves are reasonable. All test currents fall between the best and worst case curves of the slipping loss model.

Changing Area Loss Model. Instead of modeling the additional losses as the bubble height, this model assumes that the Gurney

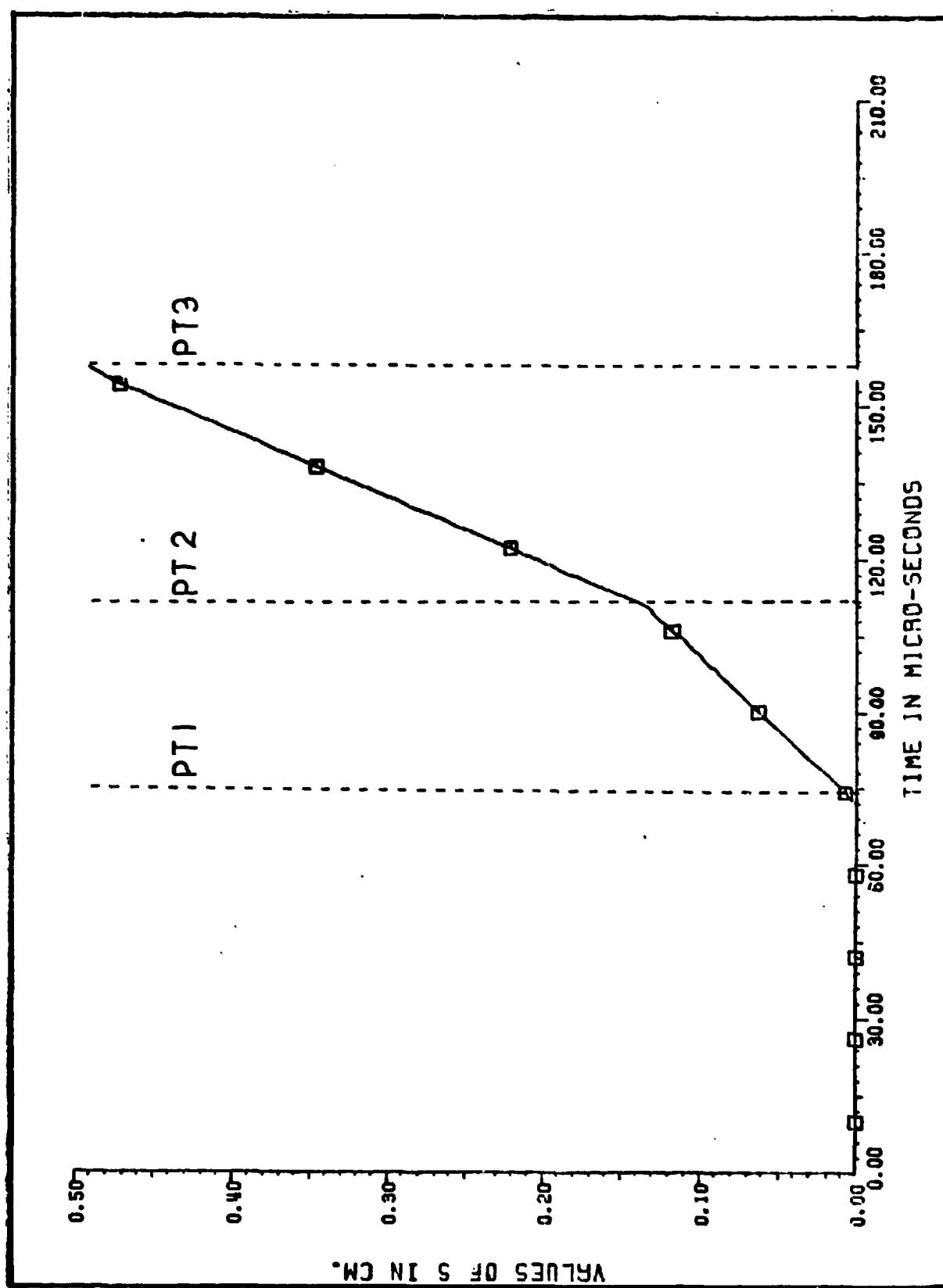
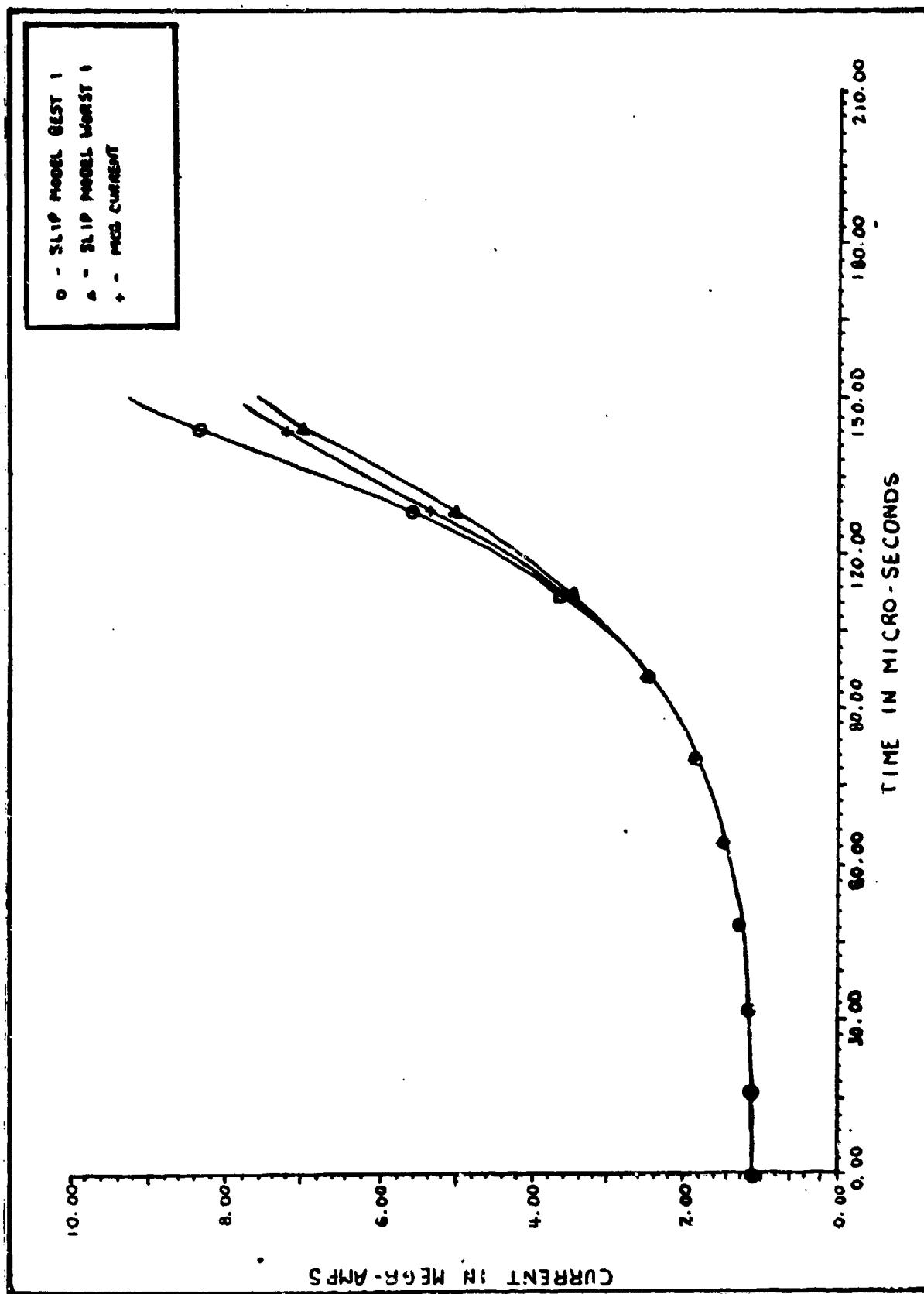


Figure 6-5. S Curve Test 1



approximations for the changing inductance are not valid. Figure 6-7 shows a plot of the additional area which must be added for the model current to match the experimental current. Points 1, 2, and 3 from Figure 3-4 are shown on this figure. Figure 6-8 shows the Gurney based area, the additional area, and the sum of these areas; similar curves for the second and third test are contained in Appendix B.

Negative areas indicate that flux compression is occurring faster than that predicted by the Gurney approximations based time varying inductance. This occurs early during generator operation. Positive areas indicate that flux compression is occurring slower than that predicted by the Gurney approximations. This occurs late during MCG operation. A momentum balance during this time period shows that the momentum of the metal plate due to the explosive initially is orders of magnitude larger than the momentum of the metal plate due to magnetic pressure. By the time the top plate has started down the jet wedge, the two momentums are essentially equal with the explosive momentum always slightly larger. This means the Gurney approximations are probably not valid during the final microseconds of generator operation.

Best and worst case changing area models were developed. The best and worst case changing area model currents for the first test are shown in Figure 6-9 while similar curves for the remaining tests are contained in Appendix B. A comparison of these curves shows that the experimental currents fall between the best and worst case curves for the first and third tests. The two curves are a bit higher than the experimental current for the second test.

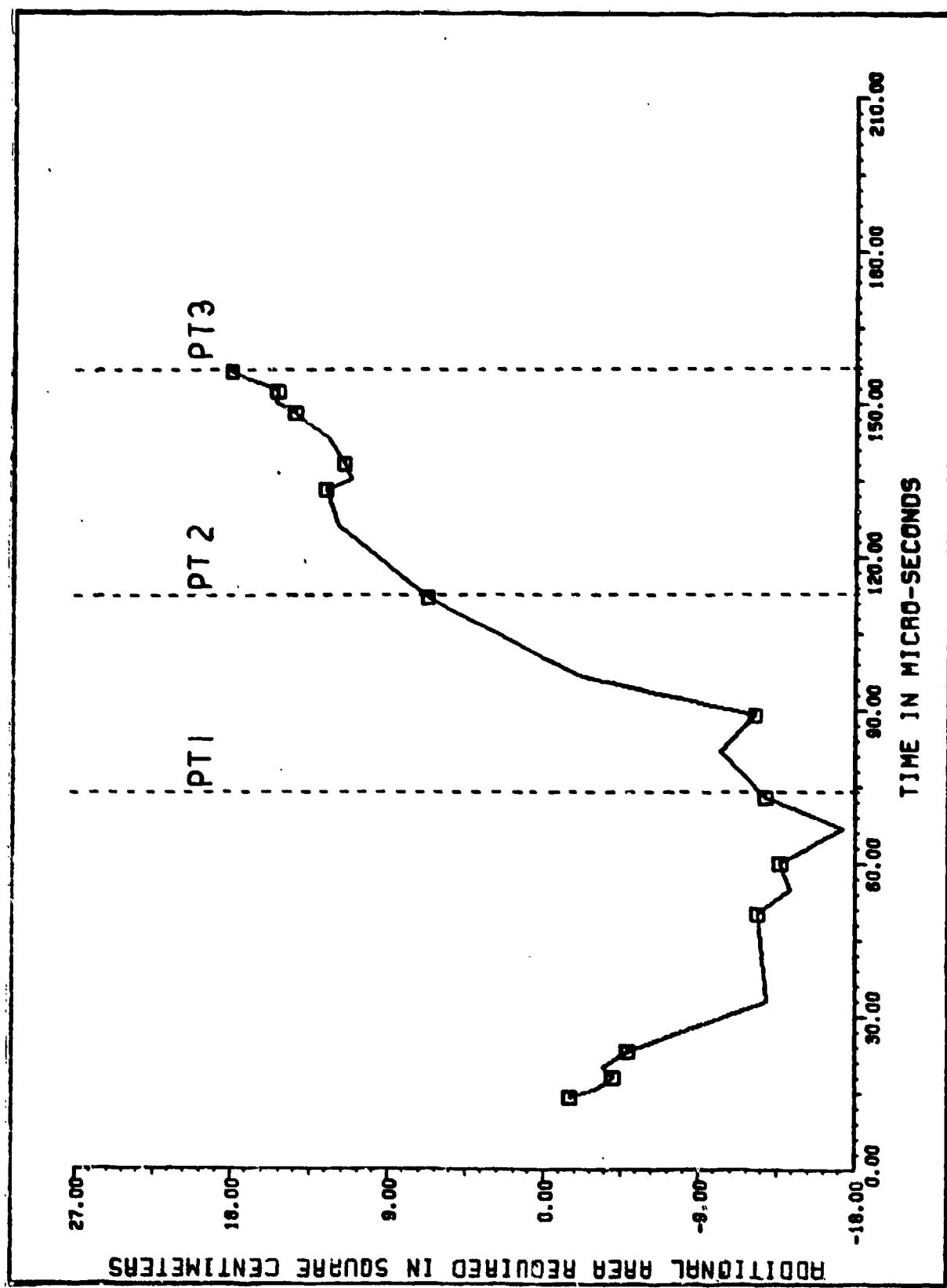
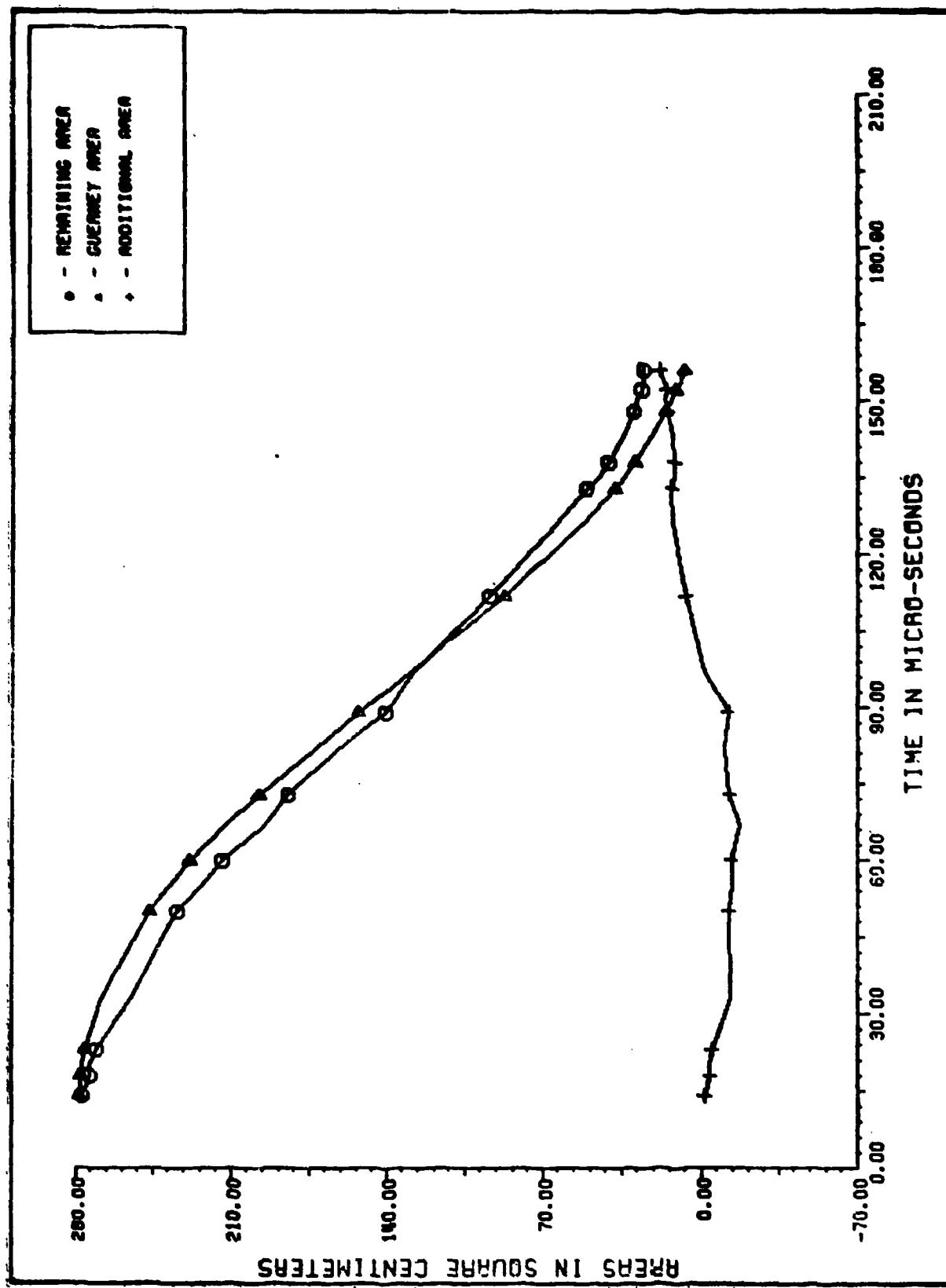


Figure 6-7. Additional Area Test 1



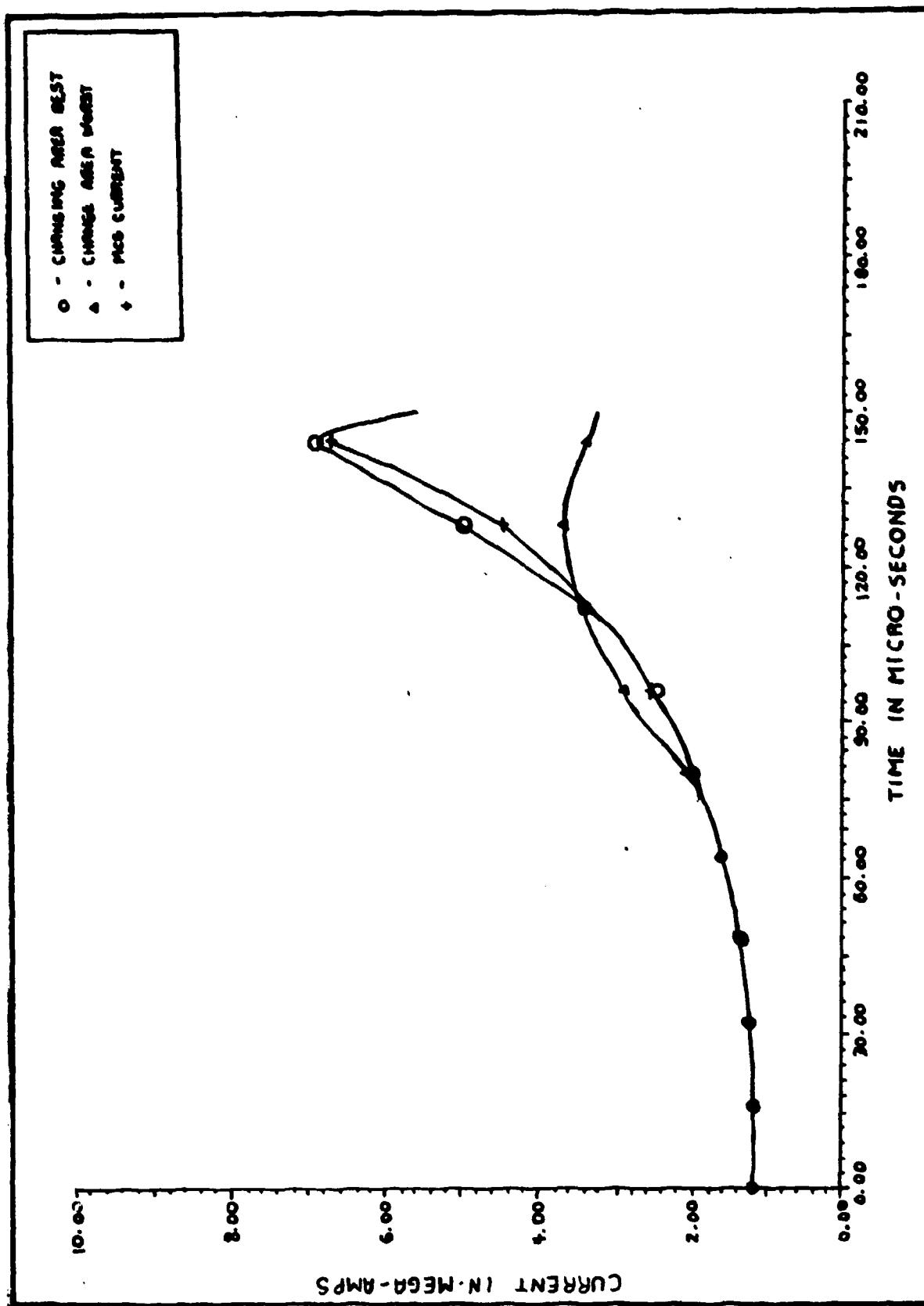


Figure 6-9. Changing Area Currents Test 1

Flux Trapping Efficiency Model. This model considers the flux trapping efficiency without regard to the flux loss mechanism. A plot of the efficiency for the first test is shown in Figure 6-10 and similar curves for the remaining tests are in Appendix B. Points 1, 2, and 3 from Figure 3-4, corresponding to key points in generator operation, are shown in this figure.

In each test, the efficiency remains better than 90% for the first half of generator operation. The values greater than 100% in the first experiment again indicate that flux compression is occurring faster than that predicted by the Gurney approximations. During the next 25% of generator operation the efficiency drops to approximately 80%. During the final 20 microseconds, severe losses occur. The final efficiency ranges between 50 and 60 percent.

The curves from the first three experiments were used to generate a best and worst case efficiency model. The plots for the best and worst case currents for the efficiency model for the first test are shown in Figure 6-11. Curves for the remaining experiments are presented in Appendix B. At the end of generation, the final currents in each test fall well within the predicted range indicating that the efficiency model is reliable.

General Results. All the models reliably predict the generator output for the first 50% of generator operation. Beyond that point only the empirical models can predict the current values. Based on the experimental data, the computer model can reliably predict the range of output currents.

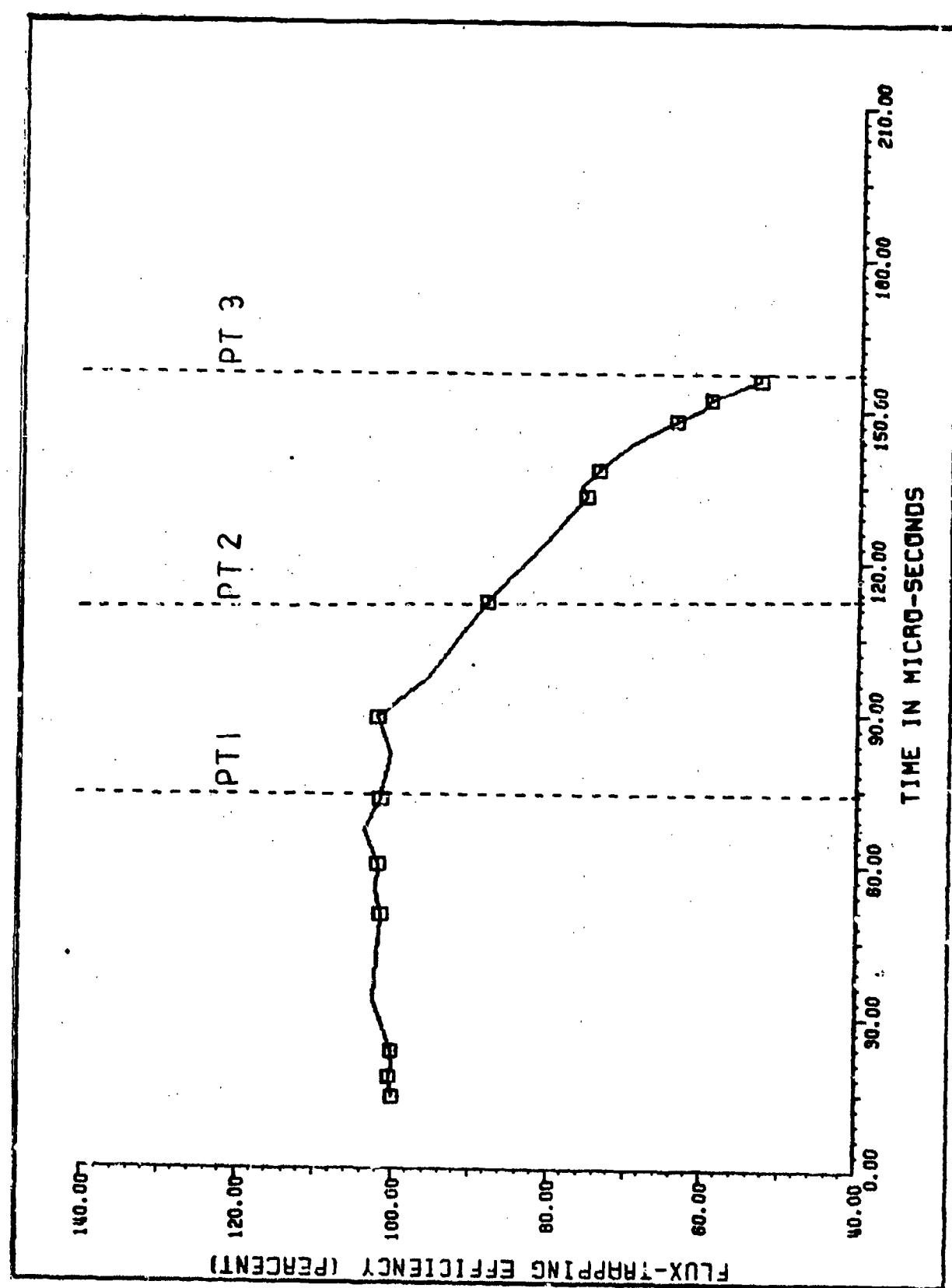


Figure 6-10. Efficiency Test 1

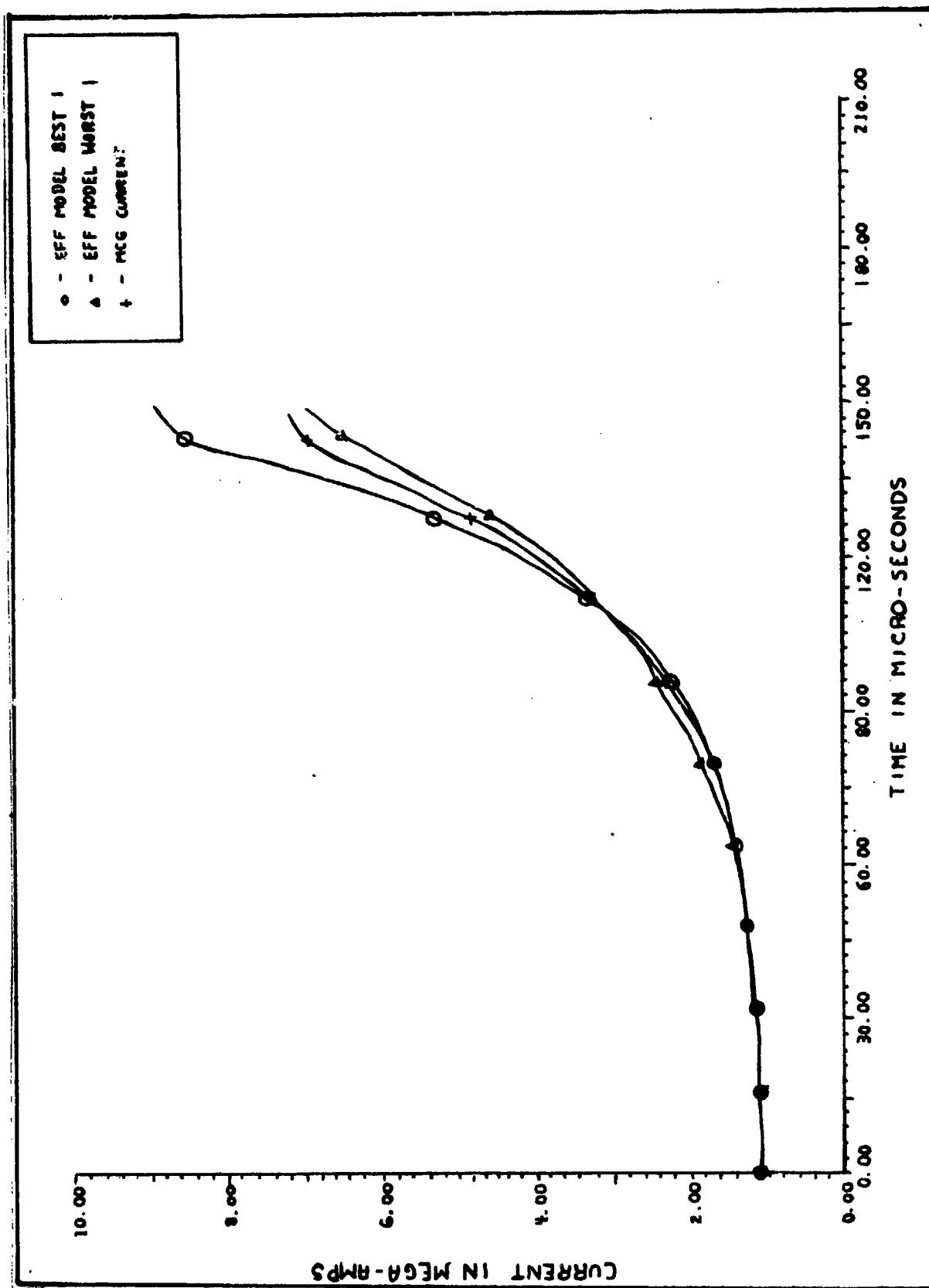


Figure 6-11. Efficiency Currents Test 1

### Conclusions

Several conclusions can be drawn:

- 1) The computer model can predict the generator output current reliably during the first 50% of operation. It can also predict the ranges in which the final maximum output current will fall;
- 2) The losses during the initial 50% of generator operation can be neglected and the generator may be considered lossless for this period;
- 3) The plate resistance and flux diffusion resistance account for only a minor portion of the loss mechanisms in generator operation;
- 4) The empirical models show that the flux compression described by the Gurney approximations is not totally accurate;
- 5) Losses are severe during the final moments of generator operation; and
- 6) The validation experiments show that the strip MCG is capable of delivering large currents over a relatively long period of time.

### Recommendations

Based on the work performed for this thesis several recommendations can be made. These include:

- 1) Computer validation of the trapezoidal portion of the computer program has never been accomplished. This portion of the program should be validated;
- 2) The empirical models are based on the results of only three tests. Further tests should be conducted to further validate them or to refine their accuracy;

- 3) Strip generators other than the AFWL MCG should be used to further validate the models (for example, different materials or dimensions);
- 4) Because the loss mechanisms in bellows generators are similar, the computer program should be expanded to include this geometry MCG;
- 5) Because the generator drives a low inductance load, the use of transformers to drive capacitive and resistive loads should be investigated and perhaps incorporated into the computer program;
- 6) Due to the momentum balances performed, tapered explosives should be considered to overcome the intense magnetic pressure as generator operation draws to an end;
- 7) When high magnetic fields and high currents were present, the load coil was visibly deformed; it opened up. This effect should be included in the computer program;
- 8) High speed photographs of generator operation should be done to gain a better understanding of how the inductance actually changes with time;
- 9) Explosive type and plate material should also be varied to further validate the computer model; and
- 10) Due to the intense magnetic pressures present near the end of generator operation, a momentum balance should be incorporated into the computer program.

## Appendix A

This appendix describes the computer program. This program is written in FORTRAN V. The inputs to the program are best described by Figure A-1.

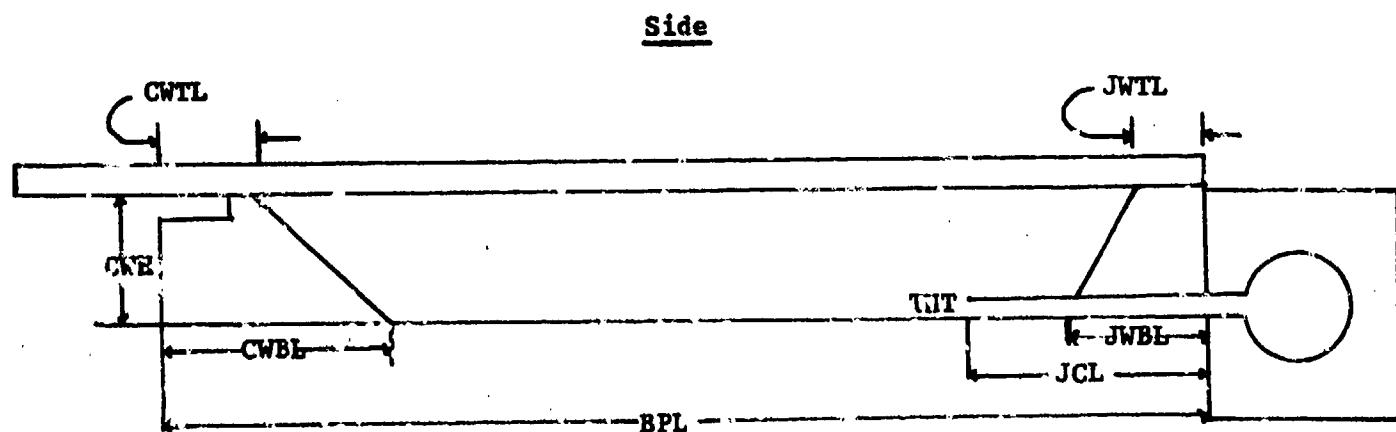
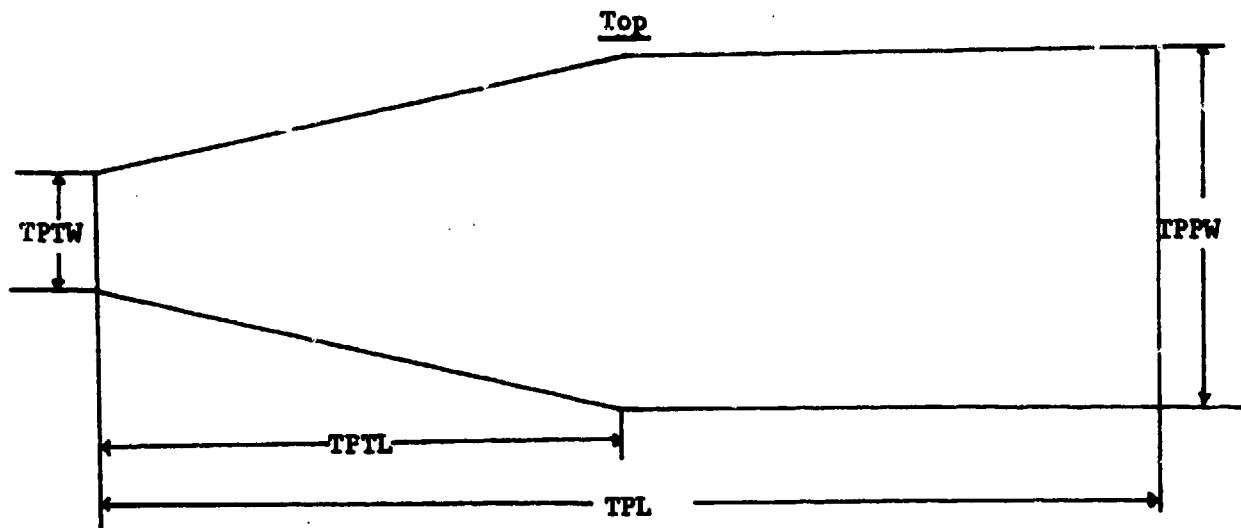


Figure A-1. Computer Inputs

### Inputs

TPPW is the parallel width of the top plate. TPTW is the trapezoidal width of the top plate at the edge. TPT is the plate thickness. TPTL is the trapezoidal length of the top plate. CPL is the total length of the top plate. TH is the height of the trough of the top plate. BPL is the length of the bottom plate. CWH is the height of the cutting wedge. CWTL is the length of the top of the cutting wedge. CWBL is the length of the bottom of the cutting wedge. JWTL is the length of the top of the jet wedge. JWBL is the length of the bottom of the jet wedge. JCL is the length of the jet catcher. TH is the throat thickness at the jet catcher. TTW is the width of the steel tamper. TTT is the thickness of the top steel tamper. TTL is the length of the steel tamper. EXPL is the weight of the explosive. CEMW is the weight of the cement brick tampers. VOLT is the capacitor bank voltage. LINEL is the line inductance. LOADL is the load inductance.

The load geometries are required for the path length calculations. They can be found using Figure A-2 as a guide. RLOAD is the radius of the load coil. For small loads RLOAD is zero. DLOAD is the depth of the load. WLOAD is the width of the load.

Two filenames are also inputs. They are the best case model results, FILNAM and the worst case model results, FNAME.

### Outputs

Outputs for this program consist primarily of currents and fields. TAMW is the total tamper mass. NTOC is the metal mass to explosive ratio. NTOC is the tamper mass to explosive ratio. The

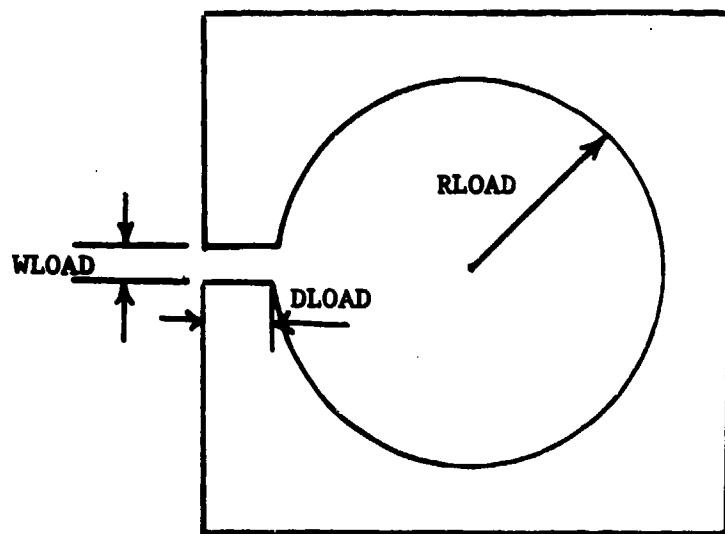


Figure A-2. Load Geometries

detonation velocity is  $D$ . The metal velocity is  $V_A$ . The Gurney angle is  $\text{THETD}$ .  $\text{TIMEI}(x)$  is the time varying Gurney inductance.  $\text{TIMEI}(x)$  is the flux conserved current.  $\text{MAGH}(x)$  and  $\text{MAGB}(x)$  are the magnetic field and the magnetic flux density respectively for the flux conserved model.  $\text{RES}(x)$  is the time varying resistance.  $\text{IRES}(x)$  is the current for the resistance model.  $\text{MAGRH}(x)$  and  $\text{MAGR}(x)$  are the magnetic field and magnetic flux density respectively for the resistance model.  $\text{ISLIP}(x)$  is the current for the sliding contact loss model.  $\text{HSLIP}(x)$  and  $\text{BSLIP}(x)$  are the magnetic field and the magnetic flux density respectively for the sliding contact loss model.  $\text{IEFF}(x)$  is the efficiency model current.  $\text{HEFF}(x)$  and  $\text{BEFF}(x)$  are the magnetic field

and magnetic flux density respectively for the efficiency model.

$IAA(x)$  is the changing area model current.  $BAA(x)$  and  $HAA(x)$  are the magnetic flux density and magnetic field respectively for the changing area model.

The program prints tabular output files of these variables. It additionally creates eight output files specifically for plotting the currents described in Chapter VI. A complete copy of the computer program can be found on the following pages.

```

*
*
*
* THIS PROGRAM CALCULATES AND PRINTS THE EXPECTED RESULTS OF A STRIP
* GENERATOR GIVEN THE BANK CAPACITANCE, LINE INDUCTANCE, LOAD INDUCTANCE,
* GENERATOR DIMENSIONS, EXPLOSIVE SIZE, AND TAMPER SIZE. AT PRESENT,
* THIS PROGRAM ASSUMES THAT THE GENERATOR IS MADE OF COPPER AND THE
* EXPLOSIVE IS DETASHEET. IF YOU WISH TO CHANGE TO ANOTHER MATERIAL OR
* EXPLOSIVE, PARAMETERS WHICH MUST BE CHANGED ARE INDICATED BY COMMENTS
* SURROUNDED BY A ROW OF *'S. THIS PROGRAM UTILIZES THE GURNEY EQUA-
* TIONS AND SIMPLE GEOMETRY. ALTHOUGH THE PROGRAM ALLOWS FOR A TRAPE-
* ZOIDAL GENERATOR, IT ASSUMES THAT THE STEEL TAMPER IS RECTANGULAR IN
* CROSS SECTION. THIS PROGRAM CALCULATES BOTH A FLUX CONSERVED MODEL
* AND A TIME VARYING RESISTANCE/INDUCTANCE MODEL BASED ON THE MAGNETIC
* SKIN DEPTH. THIS PROGRAM ALSO CALCULATES THREE EMPIRICAL MODELS, THE
* SLIPPING LOSS EMPIRICAL MODEL, THE FLUX TRAPPING EFFICIENCY MODEL, AND
* THE CHANGING AREA EMPIRICAL MODEL.
*
*
*

```

#### PROGRAM STRIP

```

INTEGER LIMIT,LIM1,LIM12,LIM2,THLM,I,J,K,L,M,N,P,Q,R,S,T,U,V
INTEGER II,JJ,KK,LL,MM,IJ,IK,CK1,CK2
REAL TPW,TPT,TPL,TTH,BPL,CWJ,CWTL,CWBL,JWTL,JWBL,JCL,TTW,TTI,TTL
REAL THT,CEM,EXPL,VOLT,CAP,LINEL,LOADL,VOL1,VOL2,PVOL,METW,TAMW
REAL TAMW,MTOC,NTOC,ANUM,ADEN,A,VM1,VM2,VM,VNUM,VDEN,THETA,ARG1,D
REAL XR,X1,XE,XF1,INTL,THROL,XSTOP,TSTOP,TPTL,TPTW,REST1,CWBM,AA
REAL ATOT,ARG2,APRIM,THETD,ALPHD,PHID,PHI,ZETA,ZETD,ZETPD,ZETAP,X
REAL LALPH,ALPHA,Y1,ASUB1,AGEN,X0,GAMAD,GAMA,ASUB2,ASUB3,LGAMA,VA
REAL XDELT,H3,CENT1,CENT2,CENT,TVL,CNUM,CDEN,IO,TOTL,IT,TPPW,BASE
REAL SBASE,SHT,TRAPA,IMHT,ZREF,CALH,CALW,XLIM2,XLIM3,B1,B2,H1,H2
REAL INTL1,INTL2,INTL3,INTL4,ANGLE,A1,LHT,VOL4,L1,L2,XLIM4,SLA1
REAL SLA2,SLA3,SLA4,SLA5,SLA6,XLIM5,XLIM1,TPPLM,LA3,RLOAD,DLOAD
REAL LLOAD,DIF,LPHI,LZET,TLOAD,PMAG,ASUB4,ASUB5,MU,REST,LITK,BB
REAL REST2,SLIPD,POWER,CONS,ROE,CC,DD,EE,FF,GG,DEC1,DEC2,DEC3
REAL DEC4,DEC5,DEC6,DEC7,D1,D2,D3,D4,LEX
REAL AREA(500),MISEC(500),TIMEI(500),W(500),LA4(500)
REAL LA5(500),LA6(500),LA4D(500),LA5D(500),LA6D(500),POS(500)
REAL LA7(500),LA7D(500),AREA1(500),AREA2(500),AREA3(500),TAU(500)
REAL ARE1D(500),ARE2D(500),ARE3D(500),TVL1(500),TVL2(500),KO(500)
REAL AREA4(500),ARE5(500),ARE4D(500),ARE5D(300),TVL4(500)
REAL TVL3(500),TLEN(500),RLEN(500),LLEN(500),BLEN(500),SIGMA(500)
REAL PATH(500),MAGB(500),MAGH(500),TVL5(500),RES(500),TEMP(500)
REAL RAV(500),LAV(500),EARG1(500),EARG2(500),IRES(500),MAGRH(500)
REAL MAGRB(500),EARG3(500),LA8(500),LA8D(500),EXPO(500),ROE(500)
REAL SMS(500),EFF(500),AAA(500),ISLIP(500),IEFF(500),IAA(500)
REAL HSLIP(500),BSLIP(500),HEFF(500),BEFF(500),HAA(500),BAA(500)
REAL SPHI(500)
CHARACTER*40 FNAME
CHARACTER*40 FILNAM
CHARACTER*40 PLOT1
CHARACTER*40 PLOT2
CHARACTER*40 PLOT3
CHARACTER*40 PLOT4

```

CHARACTER\*40 PLOTS

\* THIS PORTION OF THE PROGRAM HAS THE USER ENTER THE NEEDED PARAMETERS.  
\*  
PRINT\*, 'PLEASE ENTER THE WIDTH OF THE PARALLEL PORTION OF THE'  
PRINT\*, 'TOP PLATE IN CENTIMETERS.'>  
READ\*, TPPU  
PRINT\*, 'PLEASE ENTER THE WIDTH OF THE TOP PLATE AT THE'  
PRINT\*, 'TRAPEZOIDAL END IN CENTIMETERS.'>  
READ\*, TPTW  
PRINT\*, 'PLEASE ENTER THE THICKNESS OF THE TOP PLATE'  
PRINT\*, 'IN CENTIMETERS.'>  
READ\*, TPT  
PRINT\*, 'PLEASE ENTER THE LENGTH OF THE TRAPEZOIDAL PORTION OF THE'  
PRINT\*, 'TOP PLATE IN CENTIMETERS.'>  
READ\*, TPL  
PRINT\*, 'PLEASE ENTER THE TOTAL LENGTH OF THE TOP PLATE'  
PRINT\*, 'IN CENTIMETERS.'>  
READ\*, TPL  
PRINT\*, 'PLEASE ENTER THE HEIGHT OF THE TROUGH IN CENTIMETERS.'>  
READ\*, TH  
PRINT\*, 'PLEASE ENTER THE LENGTH OF THE BOTTOM PLATE'  
PRINT\*, 'IN CENTIMETERS.'>  
READ\*, BPL  
PRINT\*, 'PLEASE ENTER THE HEIGHT OF THE CUTTING WEDGE'  
PRINT\*, 'IN CENTIMETERS.'>  
READ\*, CLW  
PRINT\*, 'PLEASE ENTER THE LENGTH OF THE TOP BASE OF THE CUTTING'  
PRINT\*, 'WEDGE IN CENTIMETERS.'>  
READ\*, CWTL  
PRINT\*, 'PLEASE ENTER THE LENGTH OF THE BOTTOM BASE OF THE CUTTING'  
PRINT\*, 'WEDGE IN CENTIMETERS.'>  
READ\*, CWBL  
PRINT\*, 'PLEASE ENTER THE LENGTH OF THE TOP BASE OF THE JET WEDGE'  
PRINT\*, 'IN CENTIMETERS.'>  
READ\*, JWTL  
PRINT\*, 'PLEASE ENTER THE LENGTH OF THE BOTTOM BASE OF THE JET'  
PRINT\*, 'WEDGE IN CENTIMETERS.'>  
READ\*, JWBL  
PRINT\*, 'PLEASE ENTER THE LENGTH OF THE JET CATCHER'  
PRINT\*, 'IN CENTIMETERS.'>  
READ\*, JCL  
PRINT\*, 'PLEASE ENTER THE THROAT THICKNESS AT THE JET CATCHER IN'  
PRINT\*, 'CENTIMETERS.'>  
READ\*, THT  
PRINT\*, 'PLEASE ENTER THE WIDTH OF THE TOP STEEL TAMPER'  
PRINT\*, 'IN CENTIMETERS.'>  
READ\*, TTW  
PRINT\*, 'PLEASE ENTER THE THICKNESS OF THE TOP STEEL TAMPER IN'  
PRINT\*, 'CENTIMETERS.'>  
READ\*, TTT  
PRINT\*, 'PLEASE ENTER THE LENGTH OF THE TOP STEEL TAMPER'  
PRINT\*, 'IN CENTIMETERS.'>  
READ\*, TTL

```

PRINT*, 'PLEASE ENTER THE WEIGHT OF THE EXPLOSIVE IN POUNDS.>'
READ*, EXPL
PRINT*, 'PLEASE ENTER THE WEIGHT OF THE TOP CEMENT BRICKS IN'
PRINT*, 'POUNDS.>'
READ*, CEMW
PRINT*, 'PLEASE ENTER THE BANK VOLTAGE IN VOLTS.>'
READ*, VOLT
PRINT*, 'PLEASE ENTER THE BANK CAPACITANCE IN MICROFARADS.>'
READ*, CAP
CAP=CAP*1E-06
PRINT*, 'PLEASE ENTER THE LINE INDUCTANCE IN NANOHENRIES.>'
READ*, LINEL
PRINT*, 'PLEASE ENTER THE LOAD INDUCTANCE IN NANOHENRIES.>'
READ*, LOADL
PRINT*, 'PLEASE ENTER THE RADIUS OF THE LOAD IN CENTIMETERS.>'
READ*, RLOAD
PRINT*, 'PLEASE ENTER THE DEPTH OF THE LOAD IN CENTIMETERS.>'
READ*, DLOAD
PRINT*, 'PLEASE ENTER THE WIDTH OF THE LOAD IN CENTIMETERS.>'
READ*, LLOAD
LINEL=LINEL*1E-09
LOADL=LOADL*1E-09
PRINT*, 'PLEASE ENTER THE BEST RESULTS FILENAME.>'
READ (5,500) FILNAM
500 FORMAT (A40)
PRINT*, 'PLEASE ENTER THE WORST RESULTS FILENAME.>'
READ (5,500) FNAME
*
* THIS PORTION OF THE PROGRAM CALCULATES THE MASS AND TAMPER RATIOS AND
* USES THE GURNEY EQUATIONS TO DETERMINE A METAL VELOCITY.
*
VOL1=TPPW*(TPL-TPTL)*TPT
BASE=TPPW/2.0
SBASE=TPTW/2.0
SHT=BASE-SBASE
IF (SHT.EQ.0.0) THEN
  VOL2=0.0
ELSE
  TRAPA=ATAN(SHT/TPTL)
  IMHT=BASE/TAN(TRAPA)
  LHT=TPTL-IMHT
  A1=IMHT*BASE
  A2=LHT*SBASE
  VOL2=TPT*(A1-A2)
END IF
L1=SQRT((IMHT*IMHT)+(BASE*BASE))-SQRT((LHT*LHT)+(SBASE*SBASE))
L2=TPL-TPTL
VOL3=2.0*TTH*(L1+L2)*TPT
PVOL=VOL1+VOL2+VOL3
METW=(8.96*PVOL)/1000.0
CEMW=CEMW/2.20462
VOL4=TTW*TTH*TTL
TAMMW=(7.86*VOL4)/1000.0
TAMW=TAMMW+CEMW

```

```

EXPL=EXPL/2.20462
MTOC=METW/EXPL
NTOC=TAMW/EXPL
ANUM=1.8+(2.0*MTOC)
ADEN=1.8+(2.0*NTOC)
A=ANUM/ADEN
VM1=(1.8+(A*A*A))/(3.0*(1.0+A))
VM2=NTOC*A*A
VM3=MTOC
* VNUM WILL HAVE TO BE CHANGED IF THE EXPLOSIVE IS NOT DETASHEET.
* VNUM=2.27
VDEN=SQRT(VM1+VM2+VM3)
VM=VNUM/VDEN
*
* THIS PORTION OF THE PROGRAM CALCULATES THETA AND V USING KENNEDY'S
* METHOD AND THE GURNEY EQUATIONS.
*
* D WILL HAVE TO BE CHANGED IF THE EXPLOSIVE IS NOT DETASHEET.
* D=6.8
ARG1=VM/(2.0*D)
THETA=2.0*(ASIN(ARG1))
VA=D*TAN(THETA)
*
* THIS PORTION OF THE PROGRAM CALCULATES THE CHANGING WIDTH OF THE
* GENERATOR.
*
XE=BPL-CUTL-JCL
XE=XE*1E01
XSTOP=XE+((CWH*1E01)/TAN(THETA))
TSTOP=XSTOP/D
LIMIT=TSTOP+1
LIM2=2*LIMIT
TIME=0.5
DO 5 I=1,LIMIT,1
  X=D*TIME
  POS(I)=X
  XLIM1=TPTL*1E01
  IF (X.LE.XLIM1) THEN
    BASE=TPPW/2.0
    SBASE=TPTW/2.0
    SHT=BASE-SBASE
    TRAPA=ATAN(SHT/TPTL)
    IMHT=BASE/TAN(TRAPA)
    LHT=(TPTL-IMHT)*1E01
    CALW=(LHT+X)*TAN(TRAPA)
    W(I)=CALW*1E-03*2.0
  ELSE
    W(I)=TPPW*1E-02
  END IF
  TIME=TIME+1.0

```

```

5      CONTINUE
*
* THIS PORTION OF THE PROGRAM CALCULATES THE INITIAL INDUCTANCE AND THE
* THROAT INDUCTANCE.
*
      XR=CWBL-CWTL
      TPTLM=TPTL*1E01
      CWBM=CWBL*1E01
      ALPHA=ATAN(XR/CWH)
      XLIM2=(TPL-JCL)*1E01
      XLIM3=(TPL-JWBL)*1E01
      XLIM4=(TPL-JWTL)*1E01
      DO 10 J=1,LIMIT,1
      IF (TPTL.EQ.0.0) THEN
          SLA1=0.5*XR*CWH*1E-04
          X1=BPL-CWBL-JCL
          SLA2=CWH*X1*1E-04
          SLA3=CWH*(JCL-JWBL)*1E-04
          XF1=JWBL-JWTL
          SLA4=0.5*XF1*(CWH-TPT)*1E-04
          SLA5=SLA1+SLA2+SLA3+SLA4
          SLA6=JCL*THT*1E-04
      ELSE
          XR=XR*1E01
          IF (X.LE.XR) THEN
              LA4(K)=0.5*X*(X/TAN(ALPHA))*1E-06
              LA5(K)=0.0
              LA6(K)=0.0
              LA7(K)=0.0
          ELSE IF (X.LE.XLIM2) THEN
              LA4(K)=0.5*XR*(XR/TAN(ALPHA))*1E-06
              LA5(K)=(X-XR)*CWHM*1E-06
              LA6(K)=0.0
              LA7(K)=0.0
          ELSE IF (X.LE.XLIM3) THEN
              LA4(K)=0.5*XR*(XR/TAN(ALPHA))*1E-06
              LA5(K)=(XLIM2-XR)*CWHM*1E-06
              LA6(K)=(X-XLIM2)*((CWH-THT-TPT)*1E01)*1E-06
              LA7(K)=0.0
          ELSE
              ANGLE=ATAN((JWBL-JWTL)/CWH)
              H1=(X-XLIM3)*1E-01
              B1=CWH-THT-TPT
              H2=JWBL-JWTL-H1
              B2=H2/(TAN(ANGLE))
              LA4(K)=0.5*XR*(XR/TAN(ALPHA))*1E-06
              LA5(K)=(XLIM2-XR)*CWHM*1E-06
              LA6(K)=(XLIM3-XLIM2)*((CWH-THT-TPT)*1E01)*1E-06
              LA7(K)=0.5*(B1+B2)*H1*1E-04
          END IF
          XR=XR*1E-01
      END IF
      TIME=TIME+1.0
10      CONTINUE

```

```

DO 15 K=2,LIMIT,1
  L=M-1
  LA4D(1)=LA4(1)
  LA5D(1)=LA5(1)
  LA6D(1)=LA6(1)
  LA7D(1)=LA7(1)
  LA4D(K)=LA4(K)-LA4(L)
  LA5D(K)=LA5(K)-LA5(L)
  LA6D(K)=LA6(K)-LA6(L)
  LA7D(K)=LA7(K)-LA7(L)
15  CONTINUE
DO 20 M=1,LIMIT,1
  INTL1=((1.2566371*LA4D(M))/W(M))+INTL1
  INTL2=((1.2566371*LA5D(M))/W(M))+INTL2
  INTL3=((1.2566371*LA6D(M))/W(M))+INTL3
  INTL4=((1.2566371*LA7D(M))/W(M))+INTL4
20  CONTINUE
IF (TPTL.EQ.0.0) THEN
  INTL=(1.2566371*SLA5)/(TPPW*1E-02)
  INTL=INTL*1E-06
ELSE
  INTL=INTL1+INTL2+INTL3+INTL4
  INTL=INTL*1E-06
END IF
THLIM=((TPL-JCL)*1E01)/D
TIME=0.0
DO 25 N=1,LIMIT,1
  XLIM5=THLIM*D
  X=D*TIME
  IF (X.LE.XLIM5) THEN
    LAB(N)=0.0
  ELSE
    LAB(N)=(((BPL-JWBL)*1E01)-X)*(THT*1E01)*1E-06
  END IF
  TIME=TIME+1.0
25  CONTINUE
DO 30 P=2,LIMIT,1
  Q=P-1
  LABD(1)=LAB(1)
  LABD(P)=LAB(P)-LAB(Q)
30  CONTINUE
IF (TPTL.EQ.0.0) THEN
  THROL=(1.2566371*SLA6)/(TPPW*1E-02)
ELSE
  DO 35 R=1,LIMIT,1
    THROL=(1.2566371*LABD(R))/W(R)+THROL
35  CONTINUE
END IF
THROL=THROL*1E-06
*
* THIS PORTION OF THE PROGRAM CALCULATES HOW THE INDUCTANCE CHANGES
* WITH TIME. IT ASSUMES A CONSTANT DETONATION VELOCITY. IT FURTHER
* ASSUMES THAT THE METAL LINER IS TOTALLY ELASTIC AND THAT THE LOAD AND
* THROAT INDUCTANCES DO NOT VARY WITH TIME.

```

```

* XE=BPL-CWTL-JCL
XE=XE*1E01
XSTOP=XE+(((CWH-THT-TPT)*1E01)/TAN(THETA))
TSTOP=XSTOP/D
ARG2=CWH/(CWBL-CWTL)
ALPHA=ATAN(ARG2)
THETD=THETA*(180.0/3.1415927)
ALPHD=ALPHA*(180.0/3.1415927)
PHID=180.0-THETD-ALPHD
PHI=PHID*(3.1415927/180.0)
ZETA=ATAN(XF1/CWH)
ZETD=ZETA*(180.0/3.1415927)
ZETPD=90.0+ZETD
ZETAP=ZETPD*(3.1415927/180.0)
ALPHA=ALPHD*(3.1415927/180.0)
XR=CWBL-CWTL
XR=XR*1E01
X1=BPL-CWBL-JCL
XF1=JWBL-JWTL
X0=CWH/TAN(THETA)
X0=X0*1E01
LIMIT=TSTOP+1
TIME=0.0
DO 40 S=1,LIMIT,1
  X=T*TIME
  XLIM=XR+X0
  XF=(BPL-CWTL-JWTL)*1E01
  IF (TPTL.EQ.0.0) THEN
    IF (X.LE.XLIM) THEN
      LALPH=SIN(THETA)*(X/(SIN(PHI)))
      Y1=LALPH*SIN(ALPHA)
      ASUB1=0.5*X*Y1
      AGEN=(SLA5*1E06)-ASUB1
      AREA(S)=AGEN*1E-06
      MISEC(S)=TIME
    ELSE IF (X.LE.XF) THEN
      ASUB1=0.5*XLIM*CWH*1E01
      ASUB2=(X-XLIM)*CWH*1E01
      AGEN=(SLA5*1E06)-ASUB1-ASUB2
      AREA(S)=AGEN*1E-06
      MISEC(S)=TIME
    ELSE
      ASUB1=0.5*XLIM*CWH*1E01
      ASUB2=(X-XLIM)*CWH*1E01
      GAMAD=180.0-ZETPD-THETD
      GAMA=GAMAD*(3.1415927/180.0)
      XDELT=X-XF
      LGAMA=SIN(THETA)*(XDELT/SIN(GAMA))
      H3=LGAMA*SIN(GAMA)
      INT1=SQRT((LGAMA*LGAMA)-(H3*H3))
      CENT2=SQRT((XDELT*XDELT)-(H3*H3))
      CENT=CENT1+CENT2
      ASUB3=0.5*CENT*H3
  ENDIF
40 CONTINUE

```

```

ASUB4=((THT*TPT)*(JCL-JWBL)*1E02)
ASUB5=.5*(TPT*TPT*1E02)/TAN(THETA)
AGEN=(SLA3*1E05)-ASUB1-ASUB2+ASUB3-ASUB4+ASUB5
AREA(S)=AGEN*1E-06
MISEC(S)=TIME
END IF
TIME=TIME+1.0
ELSE
IF (X.LE.XLIM) THEN
LALPH=SIN(THETA)*(X/(SIN(PHI)))
Y1=LALPH*SIN(ALPHA)
ASUB1=0.5*X*Y1
AREA1(S)=ASUB1*1E-06
AREA2(S)=0.0
AREA3(S)=0.0
AREA4(S)=0.0
AREA5(S)=0.0
MISEC(S)=TIME
ELSE IF (X.LE.XF) THEN
AREA1(S)=0.5*XLIM*CWH*1E01*1E-06
AREA2(S)=(X-XLIM)*CWH*1E01*1E-06
AREA3(S)=0.0
AREA4(S)=0.0
AREA5(S)=0.0
MISEC(S)=TIME
ELSE
AREA1(S)=0.5*XLIM*CWH*1E01*1E-06
AREA2(S)=(X-XLIM)*CWH*1E01*1E-06
GAMAD=180.0-ZETPD-THETD
GAMA=GAMAD*(3.1415927/180.0)
XDELT=X-XF
LGAMA=SIN(THETA)*(XDELT/SIN(GAMA))
H3=LGAMA*SIN(GAMA)
CENT1=SQRT((LGAMA*LGAMA)-(H3*H3))
CENT2=SQRT((XDELT*XDELT)-(H3*H3))
CENT=CENT1+CENT2
AREA3(S)=0.5*CENT*H3*1E-06
AREA4(S)=((THT*TPT)*(JCL-JWBL))*1E-04
AREA5(S)=(0.5*(TPT*TPT)/TAN(THETA))*1E-04
MISEC(S)=TIME
END IF
TIME=TIME+1.0
END IF
40 CONTINUE
IF (TPTL.EQ.0.0) THEN
DO 45 T=1,LIMIT,1
TML=((1.2566371*AREA(T))/(TPPW*1E-02))*1E-06
TIME(T)=TML
45 CONTINUE
ELSE
DO 50 U=2,LIMIT,1
V=U-1
ARE1D(1)=AREA1(1)
ARE2D(1)=AREA2(1)

```

```

ARE3D(1)=AREA3(1)
ARE4D(1)=AREA4(1)
ARE5D(1)=AREA5(1)
ARE1D(U)=AREA1(U)-AREA1(V)
ARE2D(U)=AREA2(U)-AREA2(V)
ARE3D(U)=AREA3(U)-AREA3(V)
ARE4D(U)=AREA4(U)-AREA4(V)
ARE5D(U)=AREA5(U)-AREA5(V)
50    CONTINUE
DO 55 I=2,LIMIT,1
      J=I-1
      TVL1(I)=((1.2566371*ARE1D(1))/W(1))*1E-06
      TVL2(I)=((1.2566371*ARE2D(1))/W(1))*1E-06
      TVL3(I)=((1.2566371*ARE3D(1))/W(1))*1E-06
      TVL4(I)=((1.2566371*ARE4D(1))/W(1))*1E-06
      TVL5(I)=((1.2566371*ARE5D(1))/W(1))*1E-06
      TVL1(I)=(((1.2566371*ARE1D(I))/W(I))*1E-06)+TVL1(J)
      TVL2(I)=(((1.2566371*ARE2D(I))/W(I))*1E-06)+TVL2(J)
      TVL3(I)=(((1.2566371*ARE3D(I))/W(I))*1E-06)+TVL3(J)
      TVL4(I)=(((1.2566371*ARE4D(I))/W(I))*1E-06)+TVL4(J)
      TVL5(I)=(((1.2566371*ARE5D(I))/W(I))*1E-06)+TVL5(J)
55    CONTINUE
DO 60 K=1,LIMIT,1
      TVL=INTL-TVL1(K)-TVL2(K)+TVL3(K)+TVL4(K)-TVL5(K)
      TIMEL(K)=TVL
60    CONTINUE
END IF
*
* THIS PORTION OF THE PROGRAM CALCULATES AND PRINTS THE CHANGING CURRENT.
*
DO 65 L=1,LIMIT,1
      CNUM=INTL+THROL+LOADL
      CDEN=THROL+LOADL+TIMEL(L)
      TOTL=CNUM+L*INEL
      IO=VOLT*(SQRT(CAP/TOTL))
      IT=(CNUM/CDEN)*IO*1E-03
      TIMEI(L)=IT
      TIMEL(L)=TIMEL(L)*1E09
65    CONTINUE
*
* THIS PORTION OF THE PROGRAM CALCULATES THE CHANGING PATH LENGTH OF
* THE SYSTEM.
*
IF (RLOAD.EQ.0.0) THEN
      TLOAD=(2.0*3.1415927*RLOAD)+((2.0*DLOAD)+WLOAD)
ELSE
      TLOAD=(2.0*3.1415927*RLOAD)-WLOAD+(2.0*DLOAD)
END IF
TIME=0.0
DO 70 L=1,LIMIT,1
      X=D*TIME
      IF (X.LE.XLIM) THEN
          TLEN(L)=TPL-JWTL-CWTL-(X*1E-01)
          LALPH=SIN(THETA)*(X/(SIN(PHI)))*1E-01

```

```

DIF=CWBL-CWTL
LPHI=SIN(ALPHA)*(X/(SIN(PHI)))*1E-01
LLEN(L)=(SQR(((CWH*CWH)+(DIF*DIF)))-LALPH+LPHI
BLEN(L)=TPL-CWBL+TLOAD
RLEN(L)=SQR(((JWBL-JWTL)*(JWBL-JWTL))+(CWH*CWH))+JCL
ELSE IF (X.LE.XF) THEN
  TLEN(L)=TPL-JWTL-CWTL-(X*1E-01)
  LLEN(L)=CWH/SIN(THETA)
  BLEN(L)=TPL-CWTL+(CWH/TAN(THETA))+TLOAD-(X*1E-01)
  RLEN(L)=SQR(((JWBL-JWTL)*(JWBL-JWTL))+(CWH*CWH))+JCL
ELSE
  TLEN(L)=0.0
  XDELT=(X-XF)*1E-01
  GAMAD=180.0-ZETPD-THETD
  GAMA=GAMAD*(3.1415927/180.0)
  LZET=SIN(ZETAP)*(XDELT/(SIN(GAMA)))
  LLEN(L)=(CWH/SIN(THETA))-LZET
  BLEN(L)=TPL-CWTL+(CWH/TAN(THETA))+TLOAD-(X*1E-01)
  LGAMA=SIN(THETA)*(XDELT/SIN(GAMA))
  RLEN(L)=(CWH/COS(ZETA))-LGAMA+JCL
END IF
TIME=TIME+1.0
70  CONTINUE
DO 75 M=1,LIMIT,1
  PATH(M)=(TLEN(M)+LLEN(M)+RLEN(M)+BLEN(M))*1E-02
75  CONTINUE
*
* THIS PORTION OF THE PROGRAM CALCULATES THE CHANGING MAGNETIC FIELDS.
*
IF (TPTL.EQ.0.0) THEN
  DO 80 N=1,LIMIT,1
    MAGH(N)=(TIMEI(N)*1E03)/(TPPW*1E-02)
    MAGB(N)=MAGH(N)*(4.0*3.1415927*1E-09)
80  CONTINUE
ELSE
  DO 85 P=1,LIMIT,1
    MAGH(P)=(TIMEI(P)*1E03)/J(P)
    MAGB(P)=MAGH(P)*(4.0*3.1415927*1E-09)
85  CONTINUE
END IF
*
* THIS PORTION OF THE PROGRAM USES THE STRENGTH OF THE IDEAL MAGNETIC
* FIELD TO CALCULATE A CHANGING RESISTANCE BASED ON THE MAGNETIC SKIN
* DEPTH. IT FURTHER CALCULATES A RESISTANCE DUE TO THE RESISTANCE OF THE
* COPPER PLATES. IT THEN CALCULATES THE CHANGING CURRENT AND MAGNETIC
* FIELDS GENERATED FROM THIS TIME VARYING RESISTANCE.
*
* MU MAY HAVE TO BE CHANGED IF THE METAL IS NOT COPPER. ROE8 WILL HAVE
* TO BE CHANGED IF THE METAL IS NOT COPPER. LITK MAY HAVE TO BE CHANGED
* IF THE METAL IS NOT COPPER. CONS WILL HAVE TO BE CHANGED IF THE METAL
* IS NOT COPPER.
*
* MU=4.0*3.1415927*1E-07

```

```

LITK=1E-03
ROE0=1.72*1E-08
CONS=1170.0
DO 90 Q=1,LIMIT,1
  TEMP(Q)=CONS*(MAGB(Q)*MAGB(Q))
  ROE(Q)=ROE0*(1.0+(LITK*TEMP(Q)))
  SIGMA(Q)=1.0/ROE(Q)
  KO(Q)=1.0/(SIGMA(Q)*MU)
90  CONTINUE
THICK=TPT*1E-02
DO 95 R=2,LIMIT,1
  S=R-1
  TAU(R)=MAGH(R)/((MAGH(R)-MAGH(S))/((MISEC(R)-MISEC(S))*1E-06)
  SPHI(R)=2.0*SQRT((KO(R)*R*1E-06))
95  CONTINUE
DO 100 T=2,LIMIT,1
  IF (TPTL.EQ.0.0) THEN
    REST1=TAU(T)/(SIGMA(T)*MU)
    REST2=SQRT(REST1)
    REST=SIGMA(T)*REST2
    IF (SPHI(T).LE.THICK) THEN
      RES(T)=(1.0/REST)+((ROE(T)*PATH(T))/((TPPW*SPHI(T)*1E-02)))
    ELSE
      RES(T)=(1.0/REST)+((ROE(T)*PATH(T))/((TPPW*THICK*1E-02)))
    END IF
  ELSE
    REST1=TAU(T)/(SIGMA(T)*MU)
    REST2=SQRT(REST1)
    REST=SIGMA(T)*REST2
    IF (SPHI(T).LE.THICK) THEN
      RES(T)=(1.0/REST)+((ROE(T)*PATH(T))/(W(T)*SPHI(T)))
    ELSE
      RES(T)=(1.0/REST)+((ROE(T)*PATH(T))/(W(T)*THICK))
    END IF
  END IF
100  CONTINUE
RES(1)=RES(2)
DO 105 U=2,LIMIT,1
  V=U-1
  RAV(U)=(RES(U)+RES(V))/2.0
  LAV(U)=((TIME(U)+TIME(V))/2.0)*1E-09+THROL+LOADL
  EARG1(U)=(RAV(U)/LAV(U))*-1.0*1E-06
  EARG2(U)=IO*((TIME(1)*1E-09)+THROL+LOADL)/((TIME(U)*1E-09)+THROL+LOADL)
105  CONTINUE
EARG1(1)=(RES(1)/((TIME(1)*1E-09)+THROL+LOADL))*-1.0*1E-06
EARG2(1)=IO
DO 110 I=2,LIMIT,1
  J=I-1
  EARG3(1)=0.0
  EARG3(I)=EARG1(I)+EARG3(J)
110  CONTINUE
DO 115 K=1,LIMIT,1
  EXP0(K)=EXP(EARG3(K))

```

```

115  CONTINUE
    DO 120 L=1,LIMIT,1
        IRES(L)=EARG2(L)*EXP0(L)*1E-03
120  CONTINUE
    IF (TPTL.EQ.0.0) THEN
        DO 125 N=1,LIMIT,1
            MAGRH(N)=(IRES(N)/(TPPW*1E-02))*1E03
            MAGRB(N)=MAGRH(N)*(4.0*3.1415927*1E-09)
125  CONTINUE
    ELSE
        DO 130 P=1,LIMIT,1
            MAGRH(P)=(IRES(P)/W(P))*1E03
            MAGRB(P)=MAGRH(P)*(4.0*3.1415927*1E-09)
130  CONTINUE
    END IF
*
* THIS PORTION OF THE PROGRAM USES THE EMPIRICALLY DEVELOPED MODELS
* TO DESCRIBE THE CURRENT AND MAGNETIC FIELDS WHICH ACCOUNT FOR THE
* THE FLUX LOSSES DUE TO A SLIDING CONTACT, THE LOSSES DUE TO A CHANGING
* AREA, AND THE LOSSES DUE TO A FLUX TRAPPING EFFICIENCY.
*
    OPEN (UNIT=1,NAME=PLOT4,TYPE="NEW")
    WRITE (1,700)
700  FORMAT (" PLOTS OF RESISTANCE MODEL CURRENTS ")
    WRITE (1,*) LIMIT .
    DO 800 I=1,LIMIT,1
        J=I-1
        WRITE (1,*) J
800  CONTINUE
    DO 805 K=1,LIMIT,1
        A=IRES(K)*1E-03
        WRITE (1,*) A
805  CONTINUE
    CLOSE (UNIT=1)
    OPEN (UNIT=1,NAME=PLOTS,TYPE="NEW")
    WRITE (1,705)
705  FORMAT (" PLOTS OF IDEAL MODEL CURRENTS ")
    WRITE (1,*) LIMIT
    DO 810 L=1,LIMIT,1
        M=L-1
        WRITE (1,*) M
810  CONTINUE
    DO 815 N=1,LIMIT,1
        A=TIMEI(N)*1E-03
        WRITE (1,*) A
815  CONTINUE
*
* THIS PORTION OF THE PROGRAM SETS THE VALUES FOR THE BEST CASES FOR
* THE EMPIRICAL MODELS. THIS PORTION OF THE PROGRAM INITIALIZES THE
* SMALL S VALUES FOR THE BEST CASE FOR THE SLIPPING CONTACT LOSS MODEL.
*
    II=LIMIT-18
    JJ=LIMIT-81
    AA=0.3102

```

```

BB=0.2015
DEC1=BB/(II-JJ)
DEC2=(AA-BB)/(LIMIT-II)

*
* THIS PORTION OF THE PROGRAM INITIALIZES THE VALUES FOR THE BEST CASE
* EFFICIENCY MODEL.

*
CK1=1
KK=LIMIT-10
LL=LIMIT-101
CC=63.839
DD=79.056
DEC3=(DD-CC)/(LIMIT-KK)
DEC4=(100.0-DD)/(KK-LL)

*
* THIS PORTION OF THE PROGRAM INITIALIZES THE VALUES FOR THE BEST CASE
* CHANGING AREA EFFICIENCY MODEL.

*
CK2=1
MM=LIMIT-5
IJ=LIMIT-44
IK=LIMIT-81
EE=0.0009924
FF=0.0006931
GG=0.0005749
DEC5=(EE-FF)/(LIMIT-MM)
DEC6=(FF-GG)/(MM-IJ)
DEC7=GG/(IJ-IK)

*
* THE FIRST ITERATION PRODUCES THE BEST CASE PLOTS FOR THE EMPIRICAL
* MODELS. THE SECOND ITERATION PRODUCES THE WORST CASE PLOTS FOR THE
* EMPIRICAL MODELS.

*
OPEN (UNIT=1,NAME=FILNAM,TYPE='NEW')
WRITE (1,710)
710 FORMAT (' THE FOLLOWING RESULTS AND PLOTS ARE FOR THE BEST CASE ')
    IO=10*1E-03
    DO 900 I=1,2,1
*
* THIS PORTION OF THE PROGRAM CALCULATES THE SMALL S VALUES.

*
    DO 905 J=1,JJ,1
        SMS(J)=0.0
905    CONTINUE
        JJ=JJ+1
        D1=DEC1
        DO 910 K=JJ,II,1
            SMS(K)=D1
            D1=D1+DEC1
910    CONTINUE
        D2=SMS(II)+DEC2
        II=II+1
        DO 915 L=II,LIMIT,1
            SMS(L)=D2

```

```

D2=D2+DEC2
915  CONTINUE
*
* THIS PORTION OF THE PROGRAM CALCULATES THE EFFICIENCY VALUES.
*
DO 920 M=1,LL,1
EFF(M)=100.0
920  CONTINUE
D3=DEC4
LL=LL+1
DO 925 N=LL,KK,1
EFF(N)=100.0-D3
D3=D3+DEC4
925  CONTINUE
IF (CK1.EQ.1) THEN
D4=100.0-EFF(KK)-DEC3
KK=KK+1
DO 930 P=KK,LIMIT,1
EFF(P)=100.0-D4
D4=D4+DEC3
930  CONTINUE
ELSE
END IF
DO 935 Q=1,LIMIT,1
EFF(Q)=EFF(Q)/100.0
935  CONTINUE
*
* THIS PORTION OF THE PROGRAM CALCULATES THE CHANGING AREA FOR THE
* CHANGING AREA EMPIRICAL MODEL.
*
DO 940 R=1,IK,1
AAA(R)=0.0
940  CONTINUE
IK=IK+1
D5=DEC7
DO 945 S=IK,IJ,1
AAA(S)=D5
D5=D5+DEC7
945  CONTINUE
IF (CK2.EQ.1) THEN
D6=AAA(IJ)+DEC6
IJ=IJ+1
DO 950 T=IJ,MM,1
AAA(T)=D6
D6=D6+DEC6
950  CONTINUE
D7=AAA(MM)+DEC5
MM=MM+1
DO 955 U=MM,LIMIT,1
AAA(U)=D7
D7=D7+DEC5
955  CONTINUE
ELSE
END IF

```

```

* THIS PORTION OF THE PROGRAM CALCULATES THE CURRENTS DUE TO SLIPPING
* CONTACT LOSSES.
*
DO 968 V=1,LIMIT,1
IF(TPTL.EQ.0.0) THEN
  POWER=1.0-((SMS(V)*2.0)/CWH)
  ISLIP(V)=IO*((IRES(V)/IO)*POWER)
  HSLIP(V)=(ISLIP(V)/(TPPW*1E-02))*1E03
  BSLIP(V)=HSLIP(V)*MU
ELSE
  POWER=1.0-((SMS(V)*2.0)/(W(V)*1E02))
  ISLIP(V)=IO*((IRES(V)/IO)*POWER)
  HSLIP(V)=(ISLIP(V)/W(V))*1E03
  BSLIP(V)=HSLIP(V)*MU
END IF
968  CONTINUE
*
* THIS PORTION OF THE PROGRAM CALCULATES THE CURRENTS DUE TO FLUX TRAPPING
* EFFICIENCY.
*
DO 965 J=1,LIMIT,1
IF (TPTL.EQ.0.0) THEN
  IEFF(J)=EFF(J)*IRES(J)
  HEFF(J)=(IEFF(J)/(TPPW*1E-02))*1E03
  BEFF(J)=HEFF(J)*MU
ELSE
  IEFF(J)=EFF(J)*IRES(J)
  HEFF(J)=(IEFF(J)/W(J))*1E03
  BEFF(J)=HEFF(J)*MU
END IF
965  CONTINUE
*
* THIS PORTION OF THE PROGRAM CALCULATES THE CURRENTS DUE TO THE CHANGING
* AREA EMPIRICAL MODEL.
*
DO 970 K=1,LIMIT,1
IF (TPTL.EQ.0.0) THEN
  LEX=((1.2566371*AAA(K))/(TPPW*1E-02))*1E-06
  A=EXPO(K)
  B=CNUM
  C=((TIME(K)+LOADL)*1E-09)+THROL+LEX
  IAA(K)=IO*(B/C)*A
  HAA(K)=(IAA(K)/(TPPW*1E-02))*1E03
  BAA(K)=HAA(K)*MU
ELSE
  LEX=((1.2566371*AAA(K))/W(K))*1E-06
  A=EXPO(K)
  B=CNUM
  C=((TIME(K)+LOADL)*1E-09)+THROL+LEX
  IAA(K)=IO*(B/C)*A
  HAA(K)=(IAA(K)/W(K))*1E03
  BAA(K)=HAA(K)*MU
END IF

```

```

970      CONTINUE
975      WRITE (1,715)
         FORMAT (' TIME      IRES      ISLIP      IEFF      IAA')
         DO 975 L=1,LIMIT,1
            M=L-1
            WRITE (1,720) M, IRES(L), ISLIP(L), IEFF(L), IAA(L)
975      FORMAT (16,G15.4,G15.4,G15.4,G15.4)
975      CONTINUE
*
* THIS PORTION OF THE PROGRAM SETS UP THE PLOTTING FILES FOR THE SLIPPING
* CURRENT.
*
980      OPEN (UNIT=1,NAME=PLOT1,TYPE='NEW')
         WRITE (1,500) PLOT1
         WRITE (1,*) LIMIT
         DO 980 N=1,LIMIT,1
            P=N-1
            WRITE (1,*) P
980      CONTINUE
         DO 985 Q=1,LIMIT,1
            A=ISLIP(Q)*1E-03
            WRITE (1,*) A
985      CONTINUE
         CLOSE (UNIT=1)
*
* THIS PORTION OF THE PROGRAM SETS UP THE PLOTTING FILES FOR THE EFFICIENCY
* CURRENT.
*
990      OPEN (UNIT=1,NAME=PLOT2,TYPE='NEW')
         WRITE (1,500) PLOT2
         WRITE (1,*) LIMIT
         DO 990 R=1,LIMIT,1
            S=R-1
            WRITE (1,*) S
990      CONTINUE
         DO 995 T=1,LIMIT,1
            A=IEFF(T)*1E-03
            WRITE (1,*) A
995      CONTINUE
         CLOSE (UNIT=1)
*
* THIS PORTION OF THE PROGRAM SETS UP THE PLOTTING FILES FOR THE CHANGING
* AREA CURRENT.
*
1000     OPEN (UNIT=1,NAME=PLOT3,TYPE='NEW')
         WRITE (1,500) PLOT3
         WRITE (1,*) LIMIT
         DO 1000 U=1,LIMIT,1
            V=U-1
            WRITE (1,*) V
1000     CONTINUE
         DO 1005 J=1,LIMIT,1
            A=IAA(J)*1E-03
            WRITE (1,*) A

```

```

1005    CONTINUE
        CLOSE (UNIT=1)

*
* THIS PORTION OF THE PROGRAM INITIALIZES THE VALUES FOR THE WORST CASE
* FOR THE EMPIRICAL MODELS. THIS PORTION OF THE PROGRAM INITIALIZES THE
* S VALUES FOR THE SLIPPING LOSS MODEL.

*
    II=LIMIT-45
    JJ=LIMIT-84
    AA=0.4800
    BB=0.1348
    DEC1=BB/(II-JJ)
    DEC2=(AA-BB)/(LIMIT-II)

*
* THIS PORTION OF THE PROGRAM INITIALIZES THE VALUES FOR THE WORST CASE
* FOR THE EFFICIENCY MODEL.

*
    CK1=0
    KK=LIMIT
    LL=LIMIT-59
    CC=52.8528
    DEC3=0.0
    DEC4=(100.0-CC)/(LIMIT-LL)
    DD=0.0

*
* THIS PORTION OF THE PROGRAM INITIALIZES THE VALUES FOR THE WORST CASE
* FOR THE CHANGING AREA EMPIRICAL MODEL.

*
    CK2=0
    IJ=LIMIT
    IK=LIMIT-56
    EE=0.0010029
    DEC5=0.0
    DEC6=0.0
    DEC7=EE/(LIMIT-IK)
    FF=0.0
    GG=0.0
    MM=0
    OPEN (UNIT=1,NAME=FNAME,TYPE='NEW')
    WR,TE (1,725)
725    FORMAT (' THE FOLLOWING ARE THE RESULTS FOR THE WORST CASE ')
900    CONTINUE

*
* THIS PORTION OF THE PROGRAM PRINTS THE DATA DEVELOPED FOR EACH
* OF THE MODELS.

*
200    FORMAT (' THE LINE INDUCTANCE IS: ',F12.4,' NANOHENRIES')
        WRITE (1,205) INTL
205    FORMAT (' THE GENERATOR INDUCTANCE IS: ',F12.4,' NANOHENRIES')
        WRITE (1,210) LOADL
210    FORMAT (' THE LOAD INDUCTANCE IS: ',F12.4,' NANOHENRIES')
        WRITE (1,215) CAP
215    FORMAT(' THE BANK CAPACITANCE IS: ',F12.4,' MICROFARADS')
        WRITE (1,220) VOLT

```

```

220  FORMAT(' THE BANK VOLTAGE IS: ',F12.4,' KILOVOLTS')
225  WRITE (1,225) EXPL
230  FORMAT(' THERE ARE: ',F12.4,' KILOGRAMS OF EXPLOSIVES')
235  WRITE (1,230) TAMJ
240  FORMAT(' THERE ARE: ',F12.4,' KILOGRAMS OF TAMPER')
245  WRITE (1,240) MTOC
250  FORMAT(' THE MASS TO EXPLOSIVE RATIO IS: ',F12.4)
255  WRITE (1,255) NTOC
260  FORMAT(' THE TAMPER RATIO IS: ',F12.4)
265  WRITE (1,265) D
270  FORMAT(' THE DETONATION VELOCITY IS: ',F12.4,' MM/MICROSECONDS')
275  WRITE (1,275) VA
280  FORMAT(' THE METAL VELOCITY IS: ',F12.4,' MM/MICROSECONDS')
285  WRITE (1,285) THETD
290  FORMAT(' THE GURNEY ANGLE IS: ',F12.4,' DEGREES')
295  WRITE (1,295) LIMIT
300  FORMAT(' THE LIMIT IS: ',I10)
305  WRITE (1,305)
310  FORMAT(' THE RESULTS FOR THE FLUX CONSERVED MODEL ARE: ')
315  WRITE (1,315)
320  FORMAT(' TIME(MICROSECONDS)    INDUCTANCE(MANOHENRIES)')
325  DO 150 T=1,LIMIT,1
330  WRITE (1,325) MISEC(T),TIMEL(T)
335  FORMAT(' ',4X,F12.4,10X,F12.4)
340  150  CONTINUE
345  WRITE (1,345)
350  FORMAT(' TIME(MICROSECONDS)    CURRENT(KAMPS)')
355  DO 155 U=1,LIMIT,1
360  WRITE (1,360) MISEC(U),TIMEI(U)
365  FORMAT(' ',4X,F12.4,6X,F12.4)
370  155  CONTINUE
375  WRITE (1,375)
380  FORMAT(' TIME(MICROSECONDS)',10X,'HFIELD(AMPS/METER)',3X,'BFIELD(
385  +MEGAGAUSS)')
390  DO 160 V=1,LIMIT,1
395  WRITE (1,395) MISEC(V),MAGH(V),MAGB(V)
400  FORMAT(' ',4X,F12.4,4X,G20.4,2X,G20.4)
405  160  CONTINUE
410  WRITE (1,410)
415  FORMAT (' A TIME VARYING RESISTANCE IS: ')
420  WRITE (1,420)
425  FORMAT (' TIME(MICROSECONDS)    RESISTANCE(OHMS)')
430  DO 165 I=1,LIMIT,1
435  WRITE (1,435) MISEC(I),RES(I)
440  FORMAT(' ',F12.4,6X,G20.4)
445  165  CONTINUE
450  WRITE (1,450)
455  FORMAT (' THE RESULTS FOR THE TIME VARYING RESISTANCE MODEL ARE: ')
460  WRITE (1,460)
465  FORMAT (' TIME(MICROSECONDS)',3X,'CURRENT(KAMPS)')
470  DO 170 J=1,LIMIT,1
475  WRITE (1,475) MISEC(J),IRES(J)
480  FORMAT(' ',4X,F12.4,6X,F12.4)
485  170  CONTINUE

```

```

330  WRITE (1,330)
      FORMAT (' TIME(MICROSECONDS)',10X,'HFIELD(AMPS/METER)',3X,'BFIELD(
      +MEGAGAUSS)')
      DO 175 K=1,LIMIT,1
         WRITE (1,335) MISEC(K),MAGRH(K),MAGR8(K)
      335  FORMAT (' ',4X,F12.4,4X,G20.4,2X,G20.4)
175  CONTINUE
      WRITE (1,340)
340  FORMAT (' THE RESULTS FOR THE SLIPPING LOSS MODEL ARE:')
      WRITE (1,345)
345  FORMAT (' TIME(MICROSECONDS)',3X,'CURRENT(KAMPS)')
      DO 180 L=1,LIMIT,1
         WRITE (1,350) MISEC(L),ISLIP(L)
      350  FORMAT (' ',4X,F12.4,6X,F12.4)
180  CONTINUE
      WRITE (1,355)
355  FORMAT (' TIME(MICROSECONDS)',10X,'HFIELD(AMPS/METER)',3X,'BFIELD(
      +MEGAGAUSS)')
      DO 185 M=1,LIMIT,1
         WRITE (1,360) MISEC(M),HSLIP(M),BSLIP(M)
      360  FORMAT (' ',4X,F12.4,4X,G20.4,2X,G20.4)
185  CONTINUE
      WRITE (1,365)
365  FORMAT (' THE RESULTS FOR THE EFFICIENCY MODEL ARE:')
      WRITE (1,370)
370  FORMAT (' TIME(MICROSECONDS)',3X,'CURRENT(KAMPS)')
      DO 190 N=1,LIMIT,1
         WRITE (1,375) MISEC(N),IEFF(N)
      375  FORMAT (' ',4X,F12.4,6X,F12.4)
190  CONTINUE
      WRITE (1,380)
380  FORMAT (' TIME(MICROSECONDS)',10X,'HFIELD(AMPS/METER)',3X,'BFIELD(
      +MEGAGAUSS)')
      DO 195 P=1,LIMIT,1
         WRITE (1,385) MISEC(P),HEFF(P),BEFF(P)
      385  FORMAT (' ',4X,F12.4,4X,G20.4,2X,G20.4)
195  CONTINUE
      WRITE (1,390)
390  FORMAT (' THE RESULTS FOR THE CHANGING AREA LOSS MODEL ARE:')
      WRITE (1,395)
395  FORMAT (' TIME(MICROSECONDS)',3X,'CURRENT(KAMPS)')
      DO 600 Q=1,LIMIT,1
         WRITE (1,400) MISEC(Q),IAA(Q)
      400  FORMAT (' ',4X,F12.4,6X,F12.4)
600  CONTINUE
      WRITE (1,405)
405  FORMAT (' TIME(MICROSECONDS)',10X,'HFIELD(AMPS/METER)',3X,'BFIELD(
      +MEGAGAUSS)')
      DO 605 R=1,LIMIT,1
         WRITE (1,410) MISEC(R),HAA(R),BAA(R)
      410  FORMAT (' ',4X,F12.4,4X,G20.4,2X,G20.4)
605  CONTINUE
      END

```

## Appendix B

Appendix B contains the curves of the measured and calculated data used for analysis in Chapter VI. The curves for Test 1 were presented in Chapter VI. This appendix contains the same curves for the remaining tests. They include the experimental currents, the bubble heights, efficiencies, and additional areas. Also included are the output currents of each of these models.

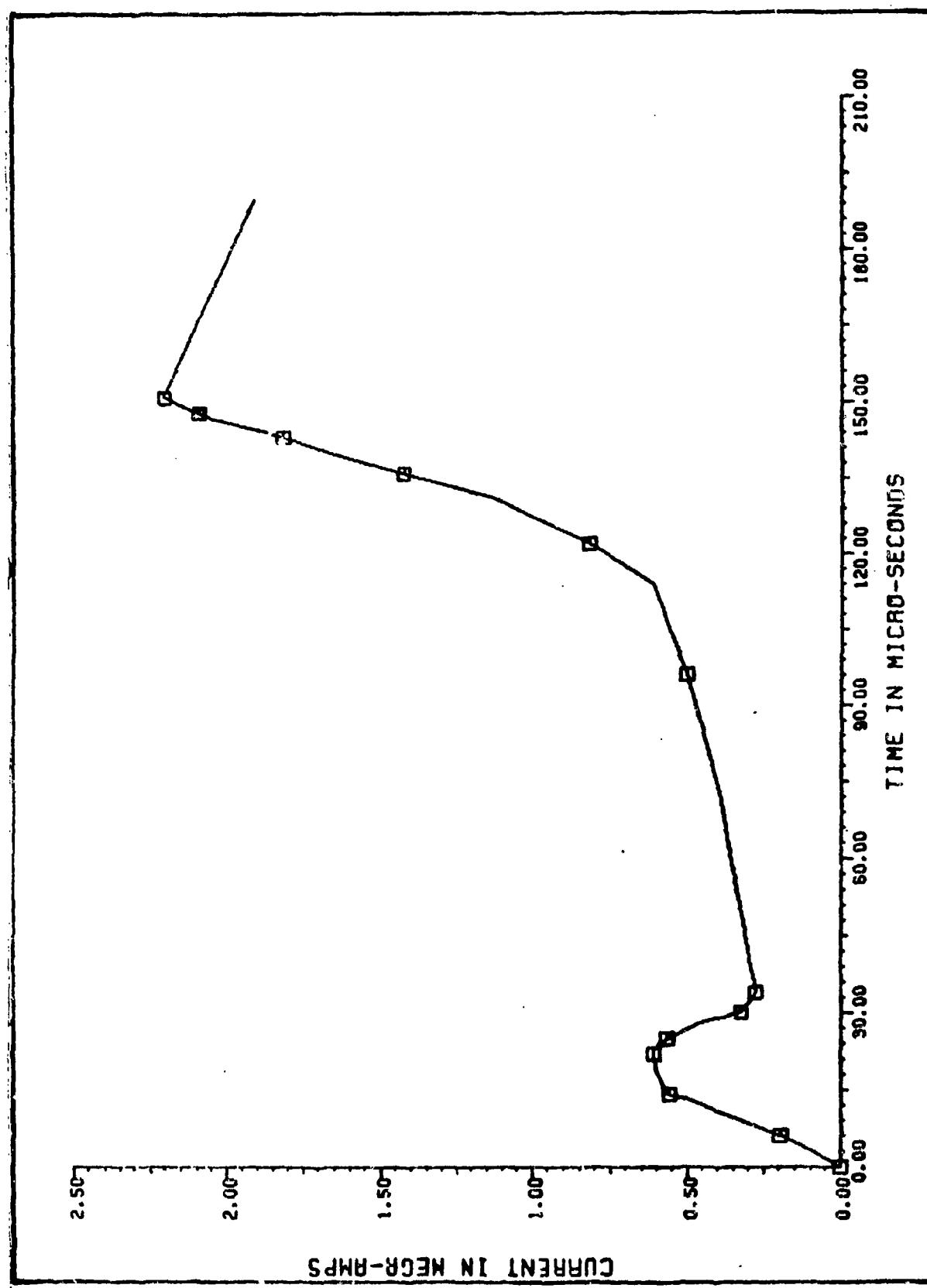


Figure B-1. Experimental Current Test 2

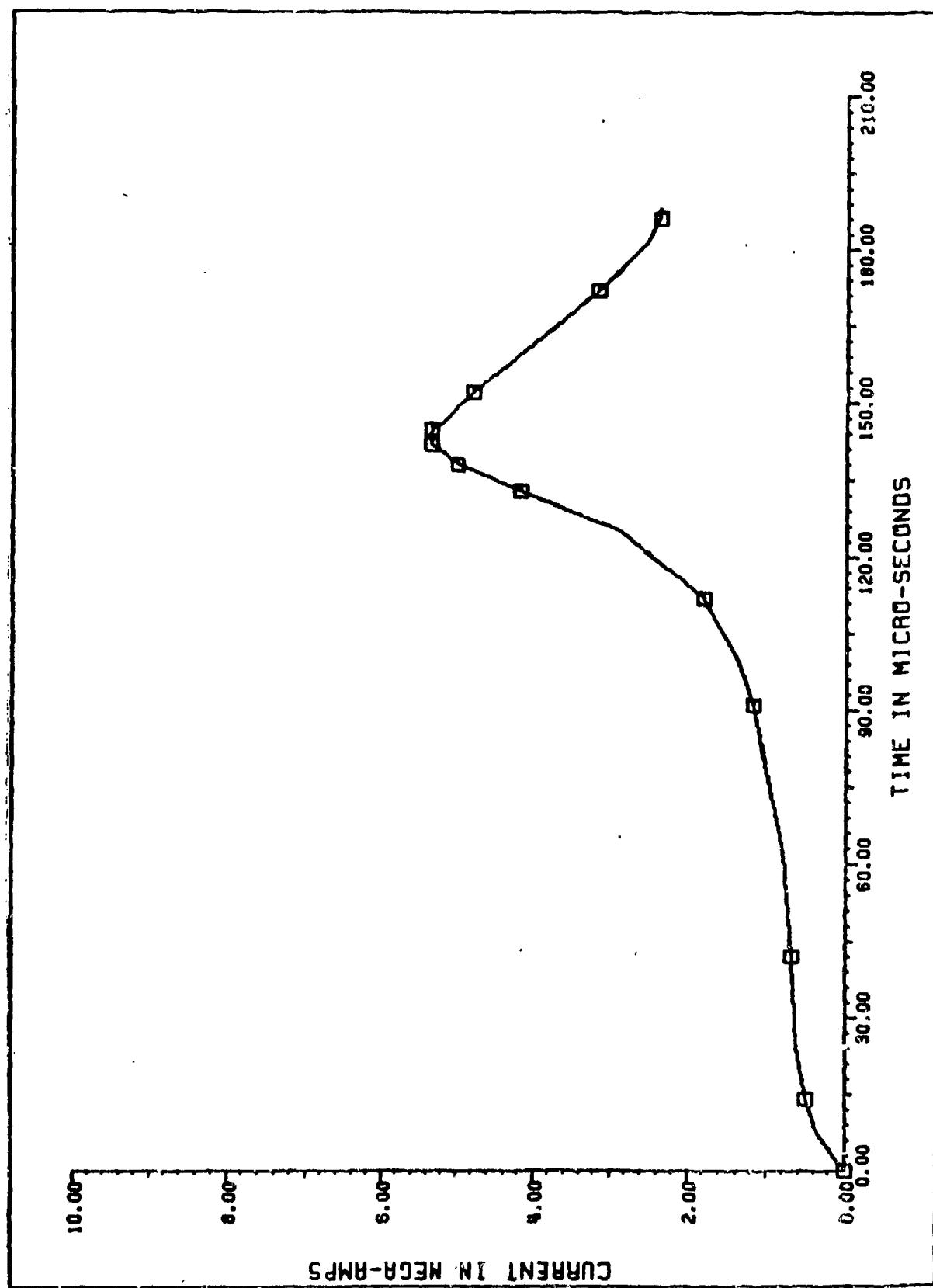


Figure B-2. Experimental Current Test 3

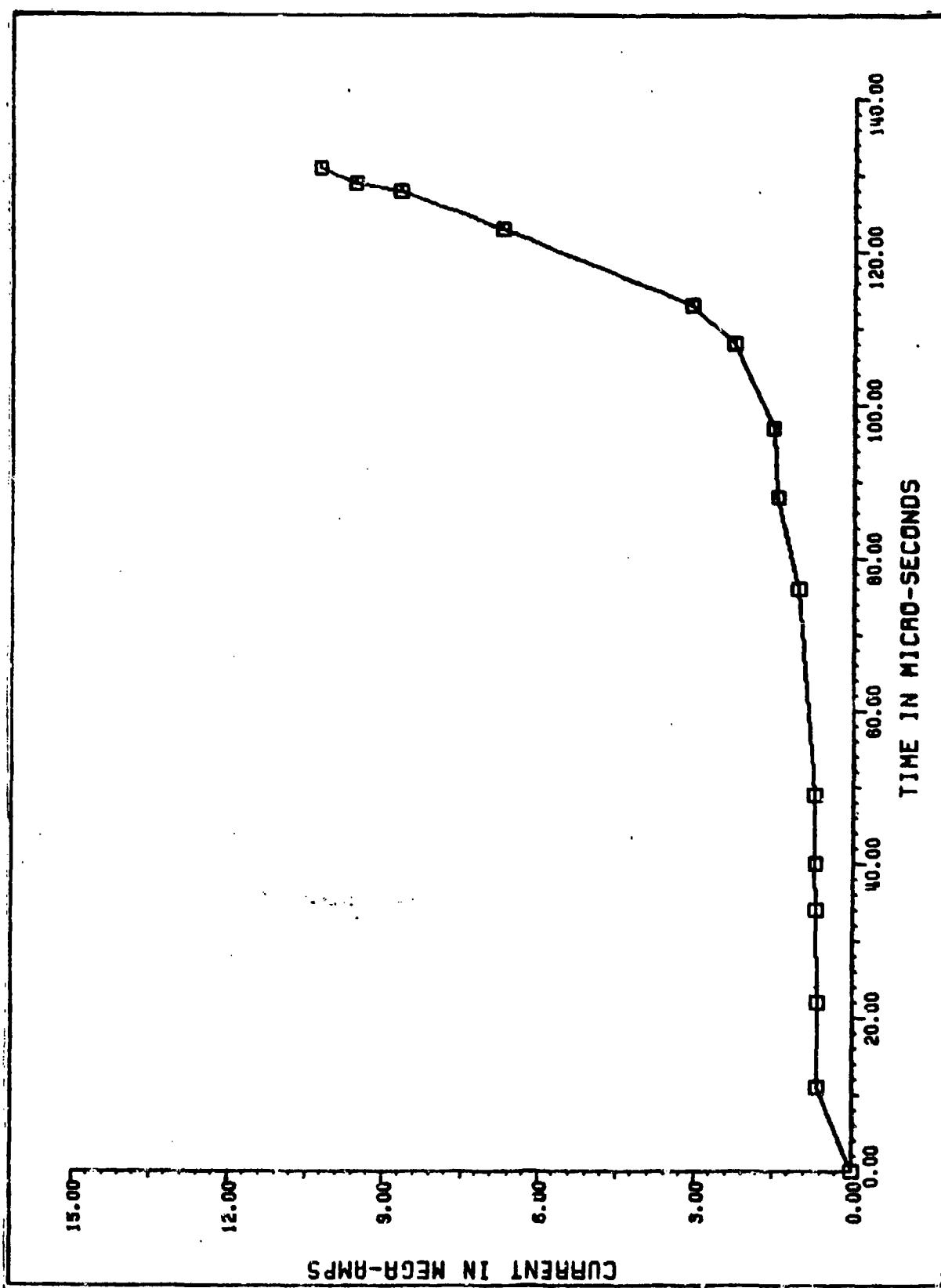


Figure B-3. Experimental Current Test 4

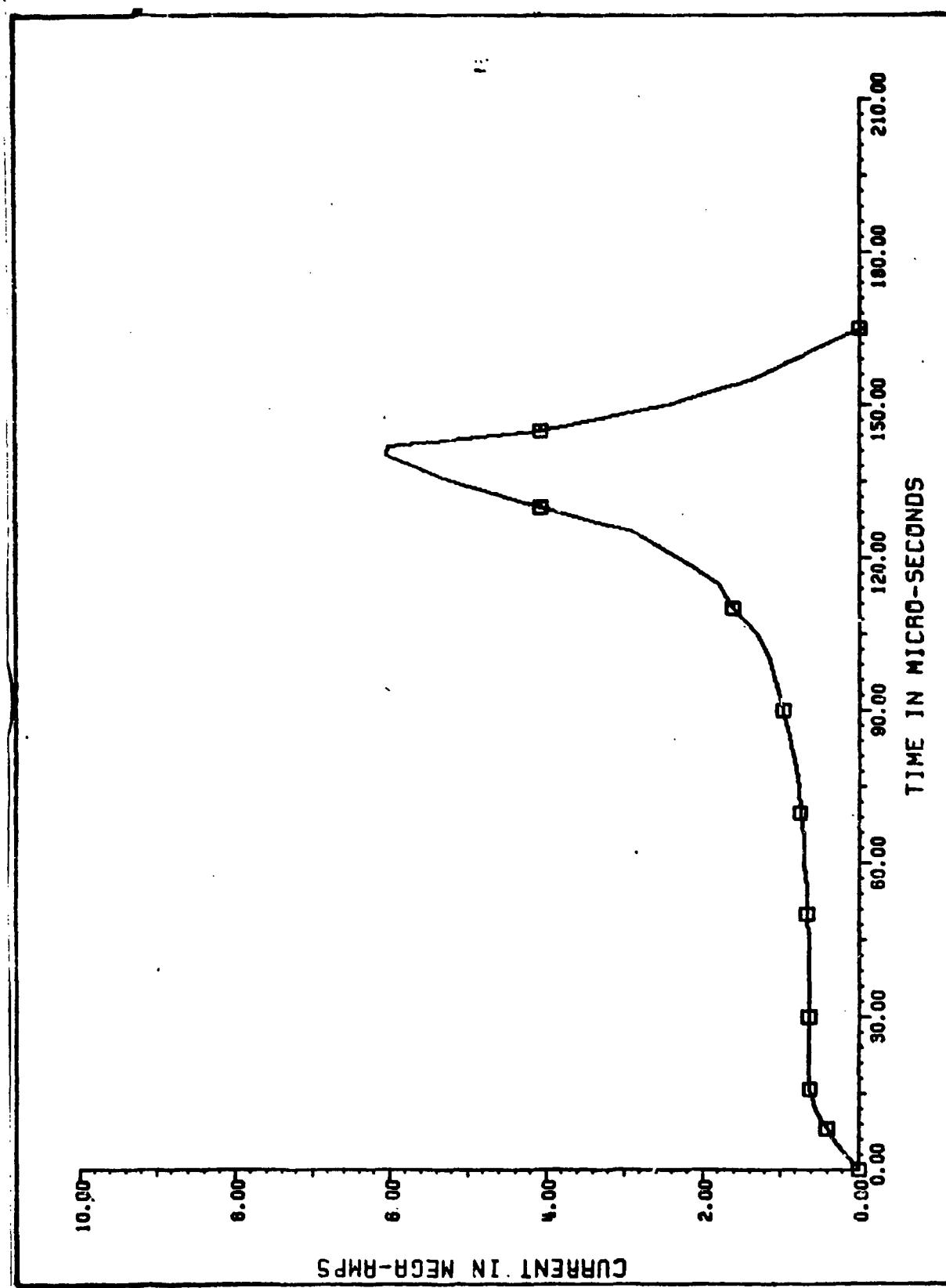


Figure B-4. Experimental Current Test 5

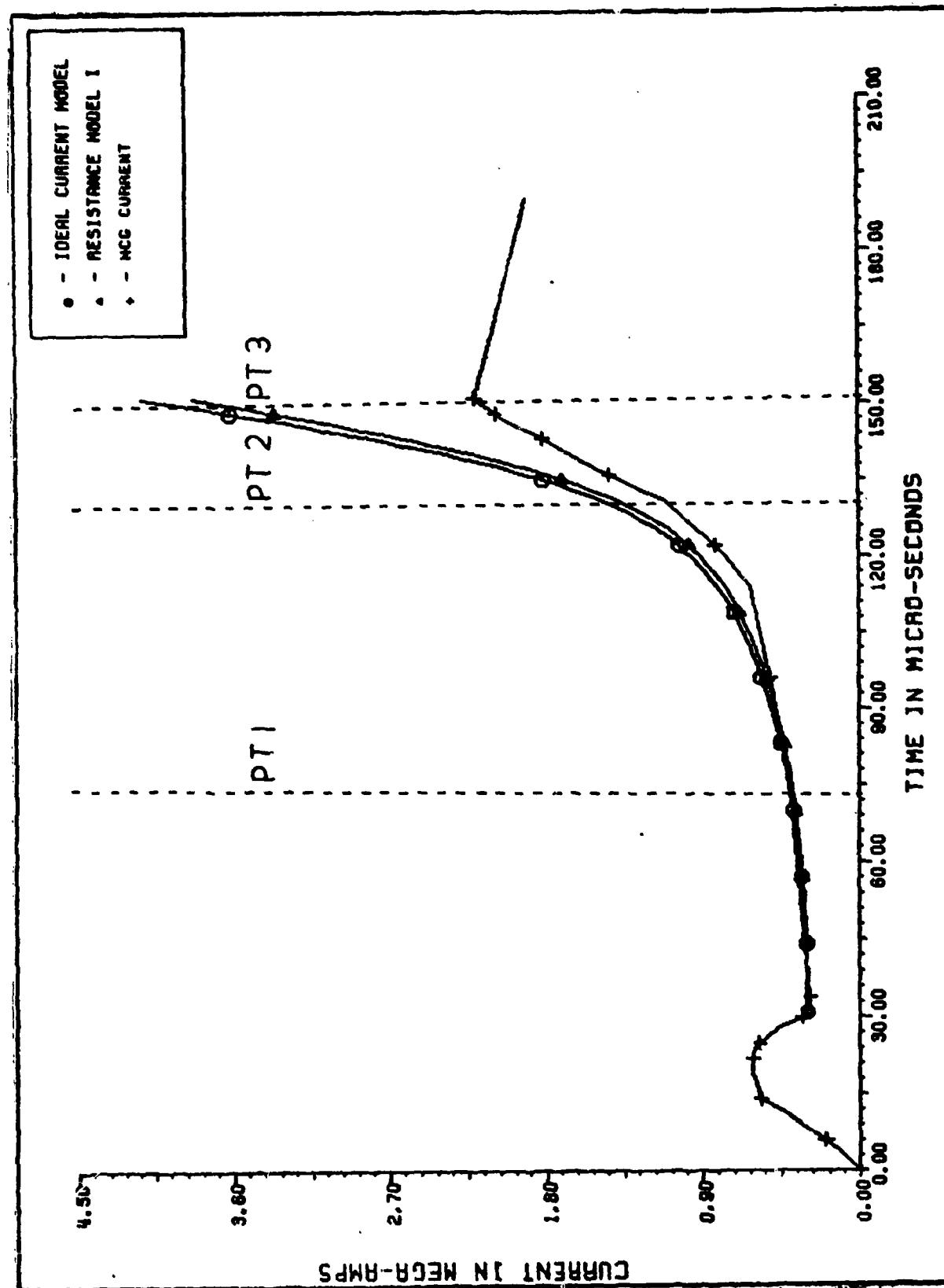


Figure B-5. Equivalent Circuit Currents Test 2

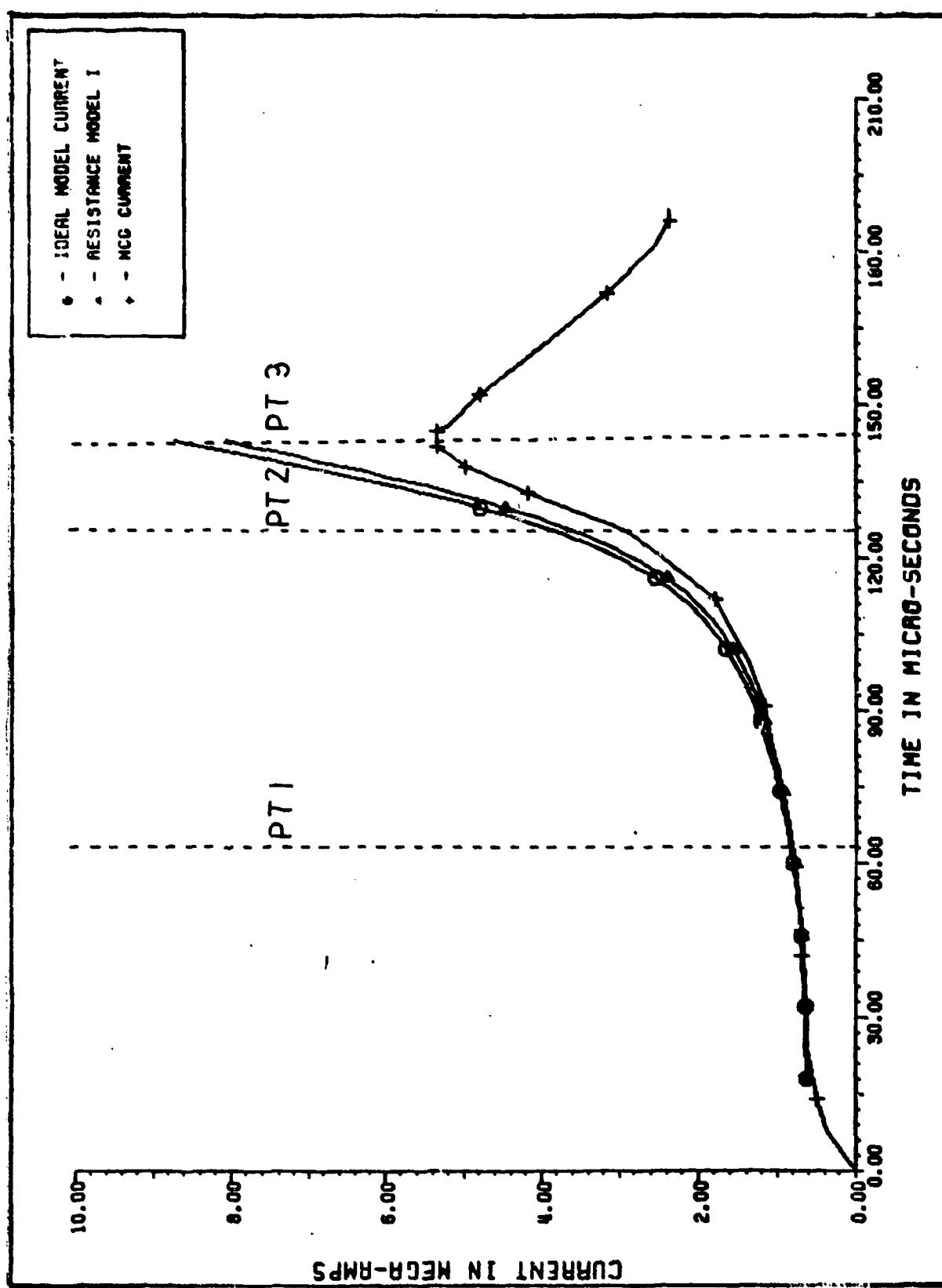


Figure B-6. Equivalent Circuit Currents Test 3

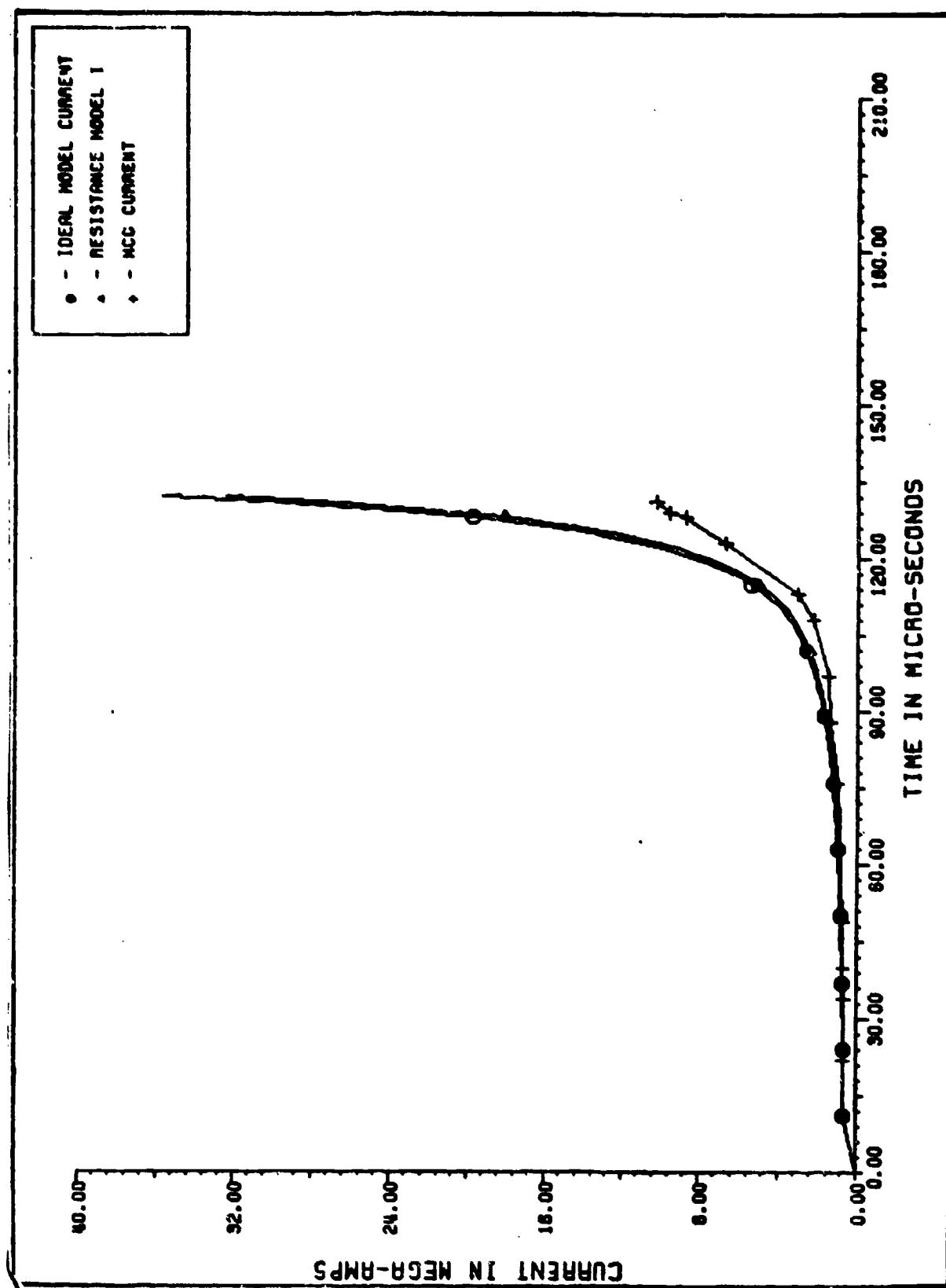


Figure B-7. Equivalent Circuit Currents Test 4

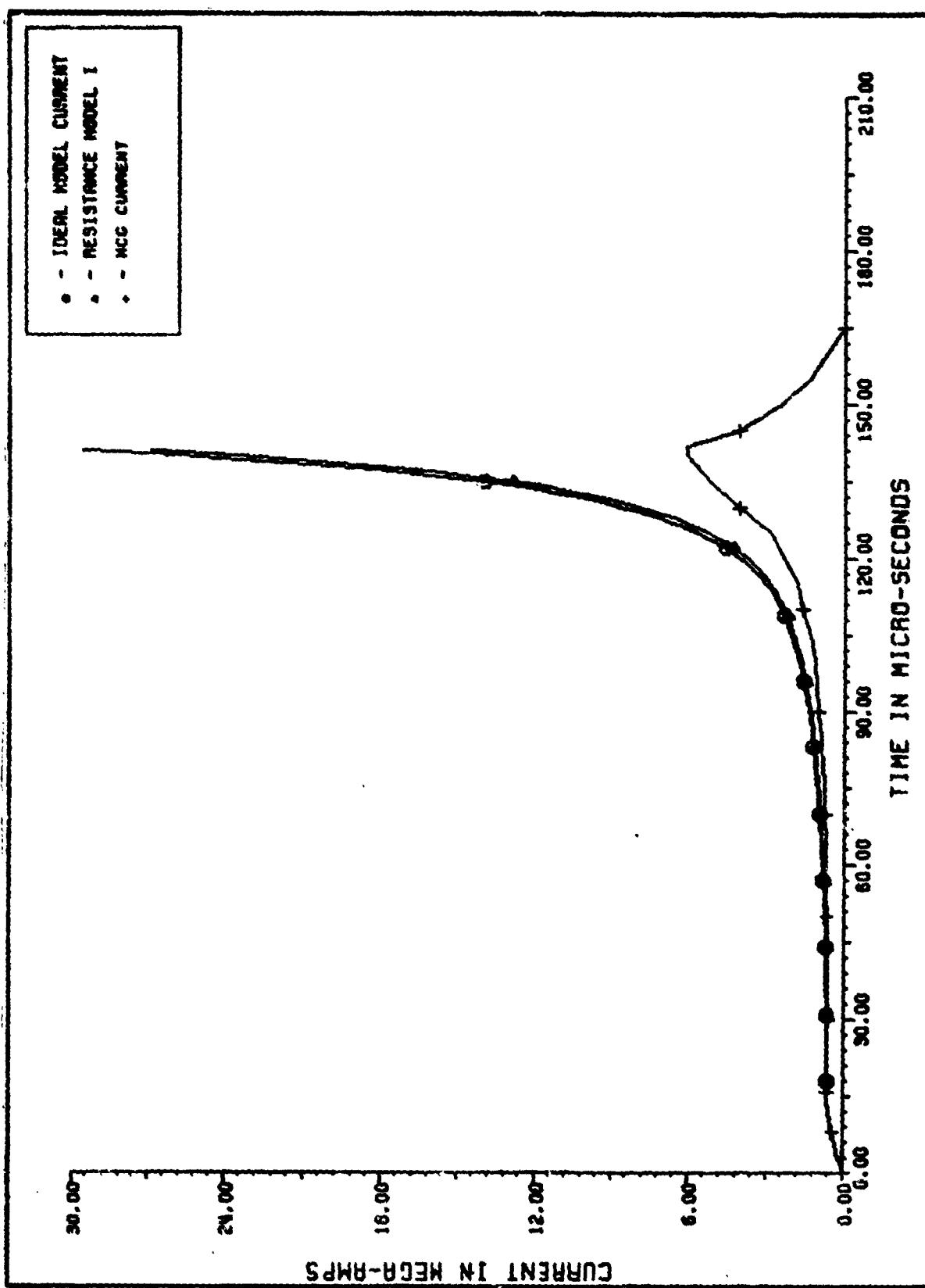


Figure B-8. Equivalent Circuit Currents Test 5

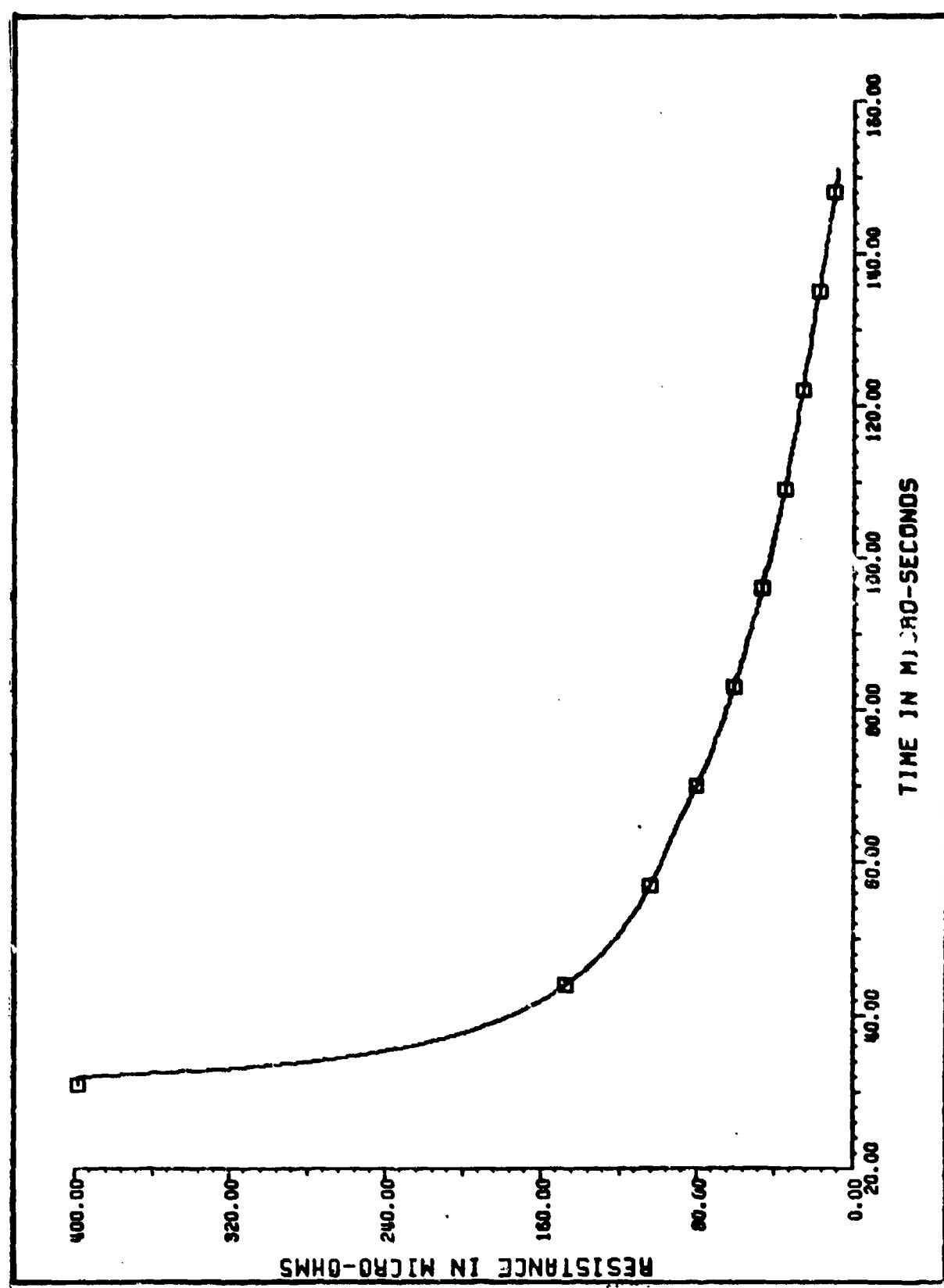


Figure B-9. Time Varying Resistance Test 2

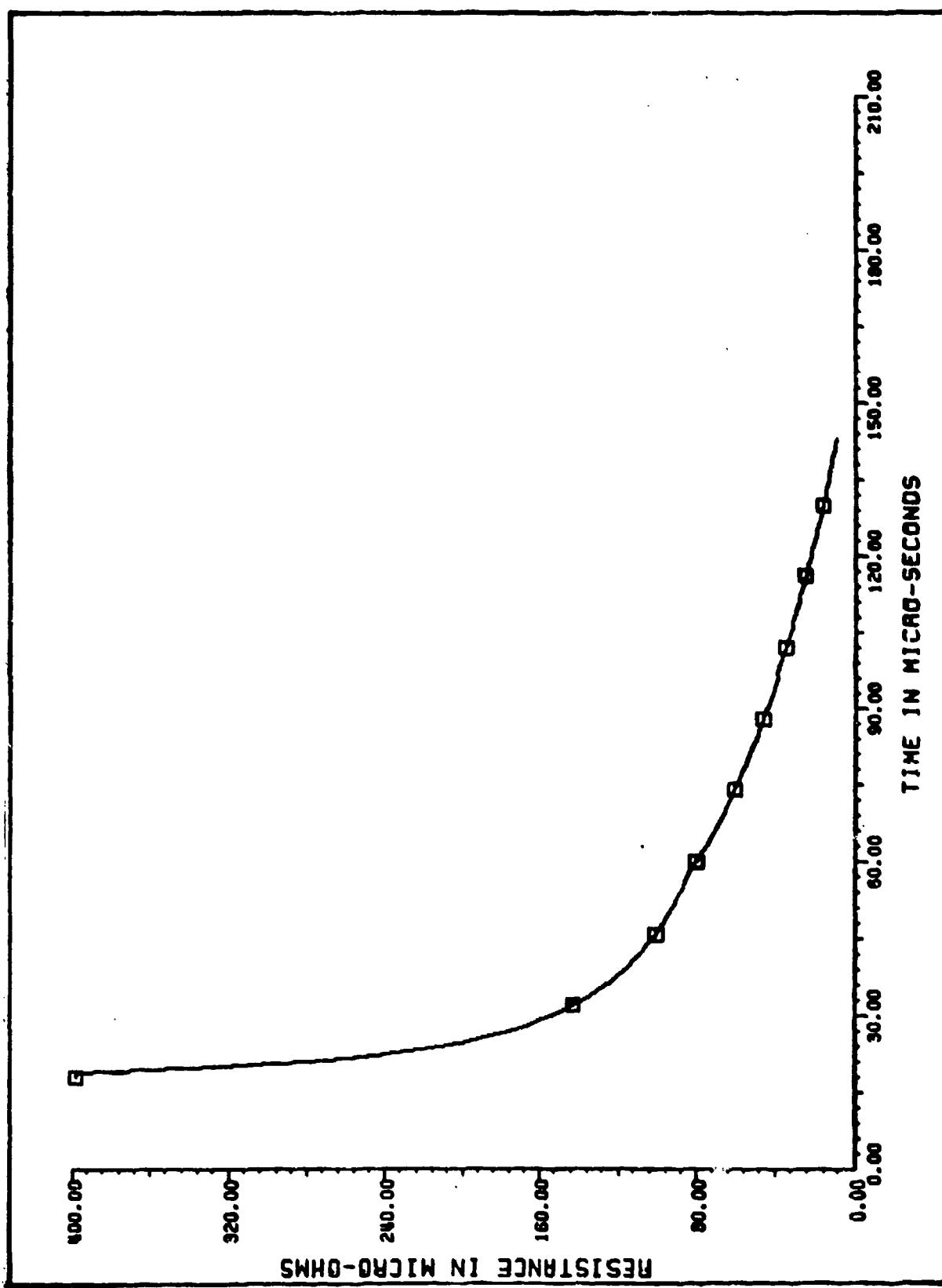
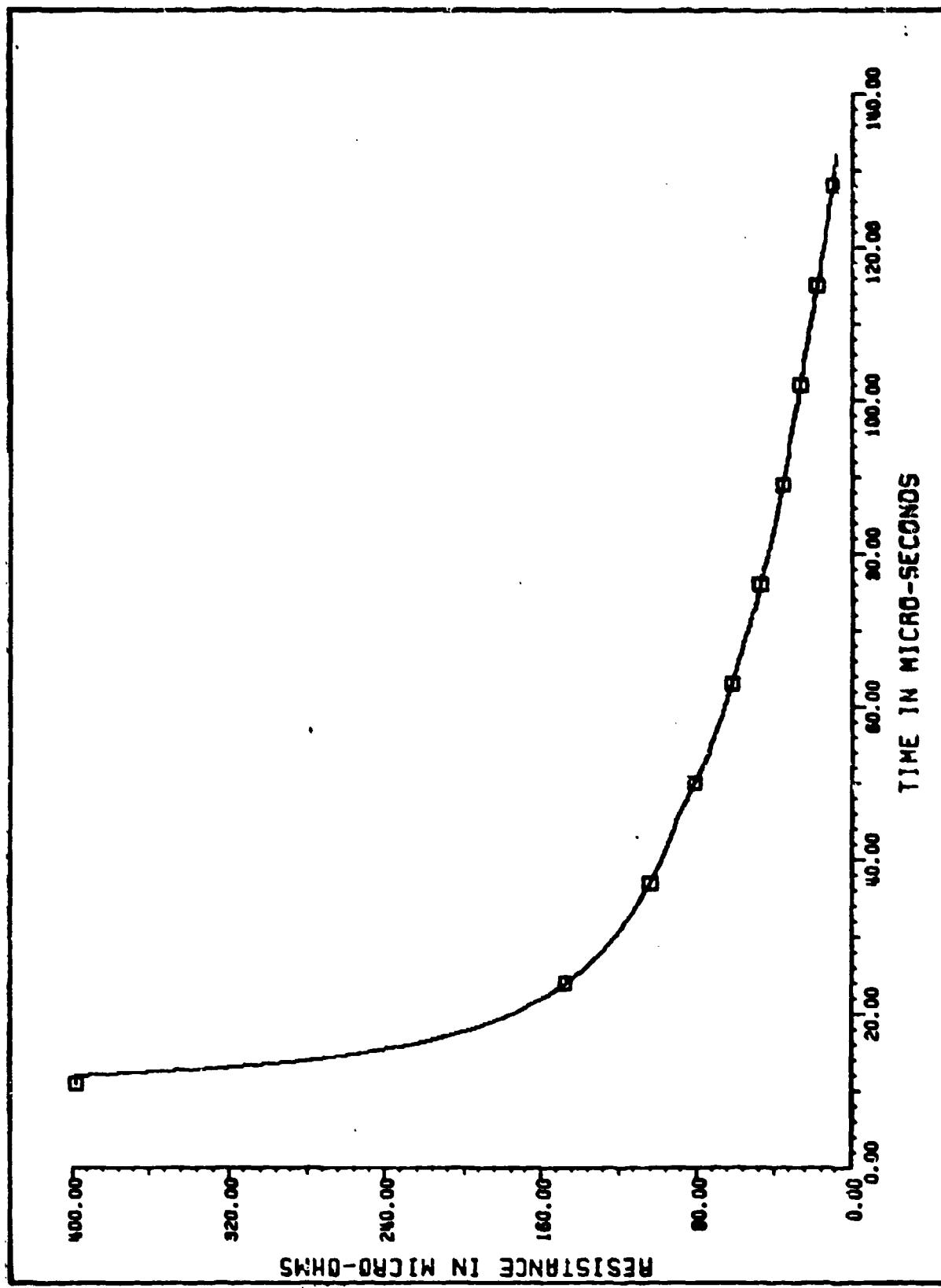
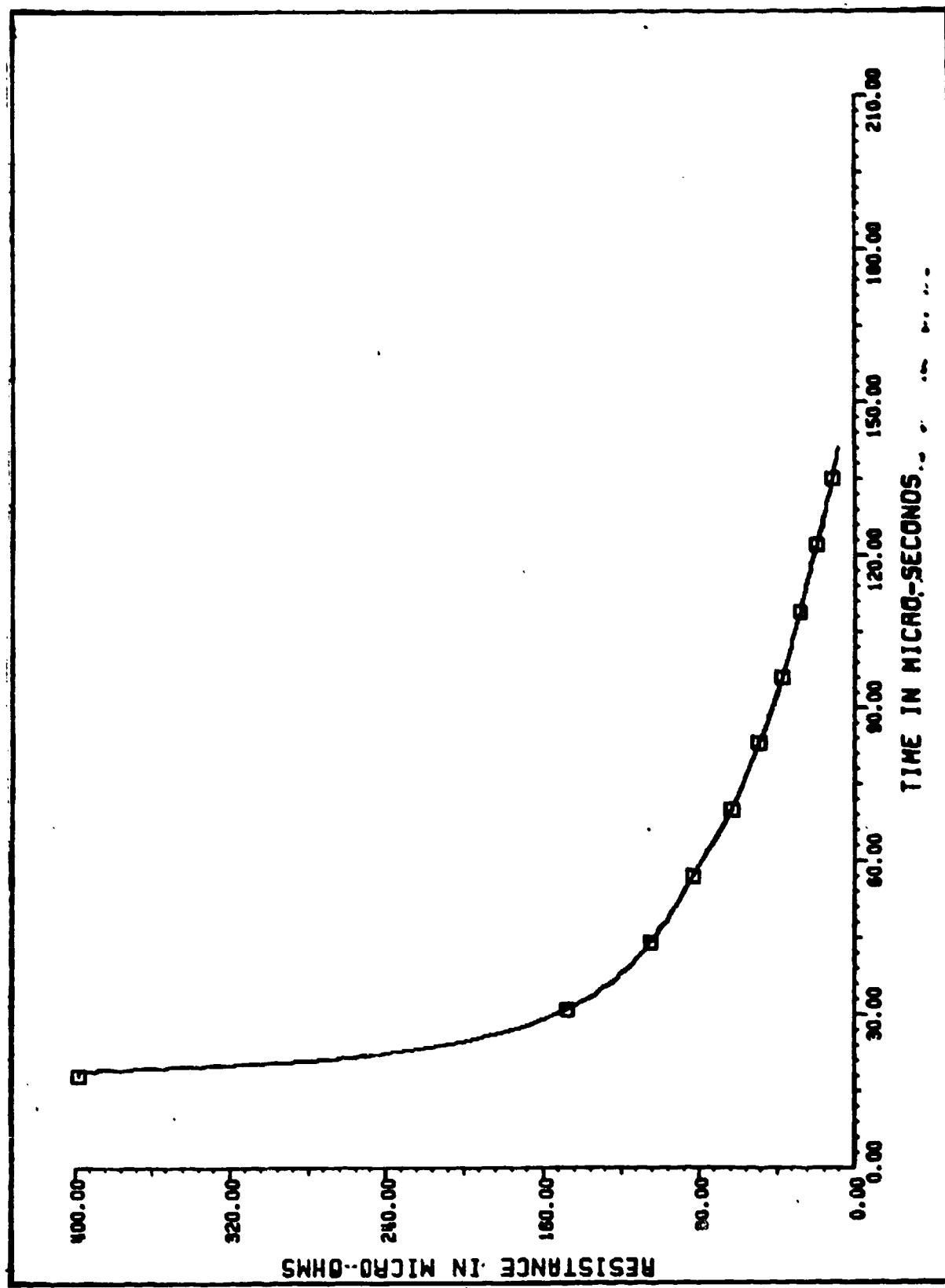


Figure B-10. Time Varying Resistance Test 3





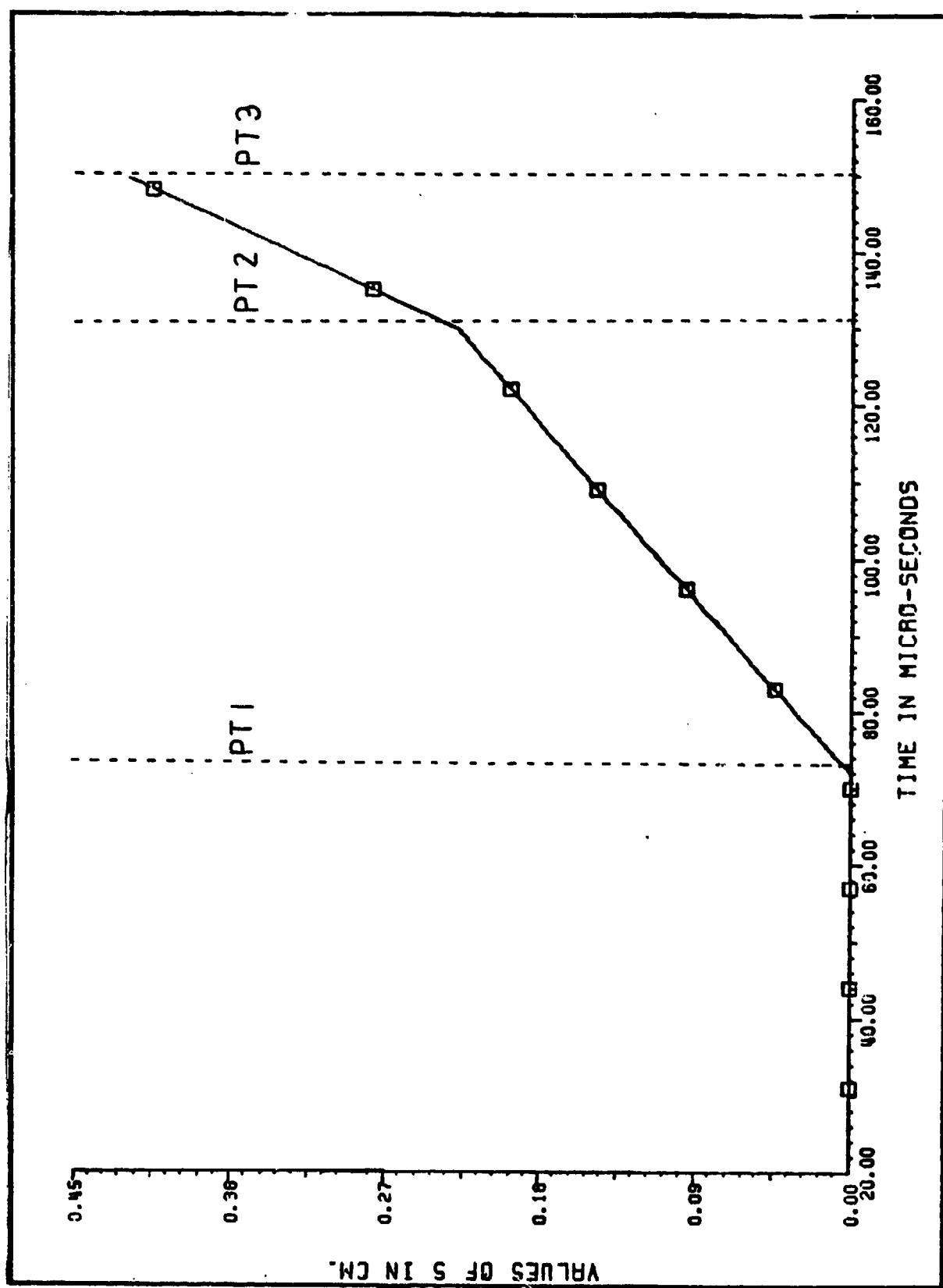


Figure B-13. S Curve Test 2

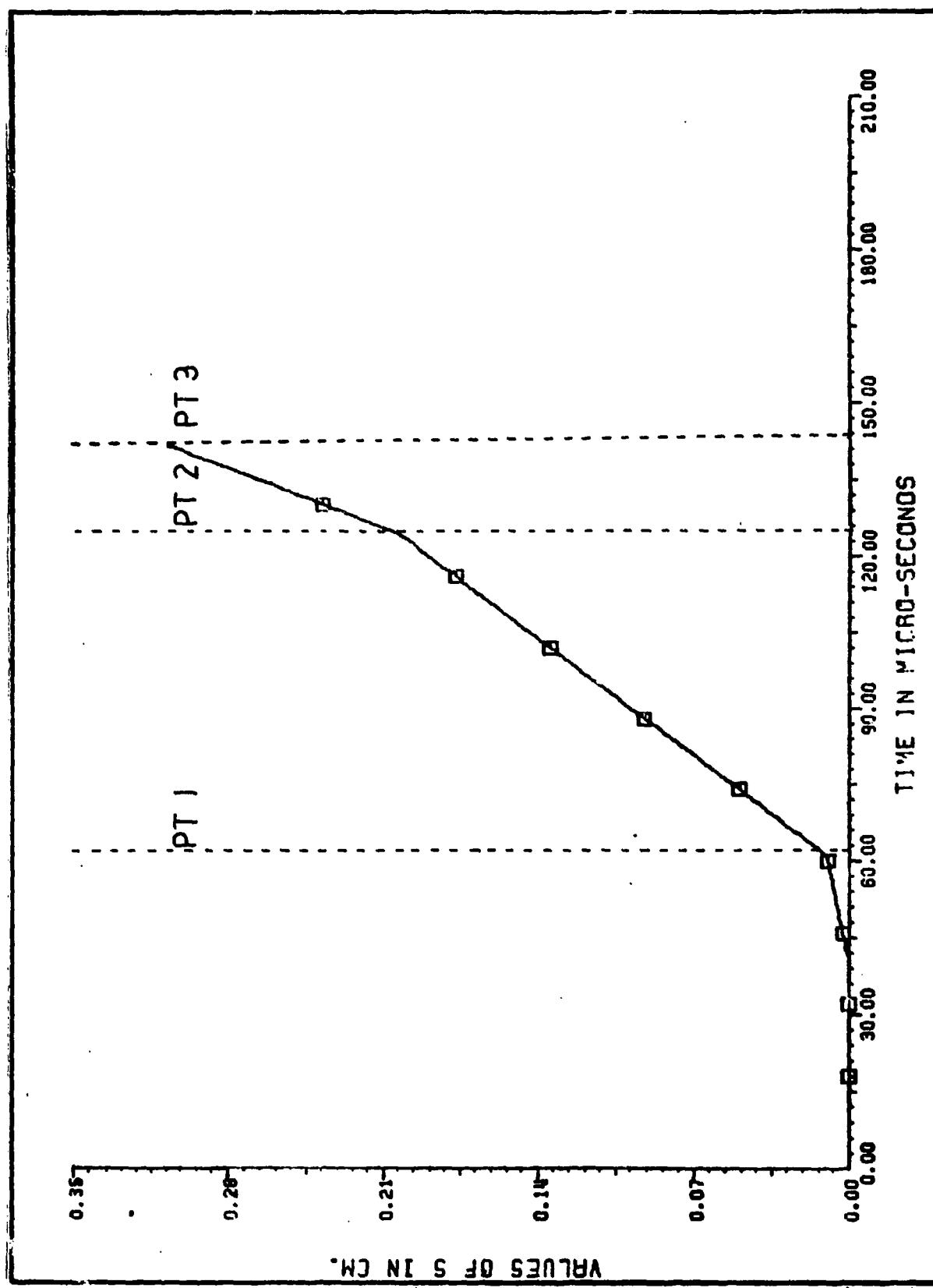


Figure B-14. S Curve Test 3

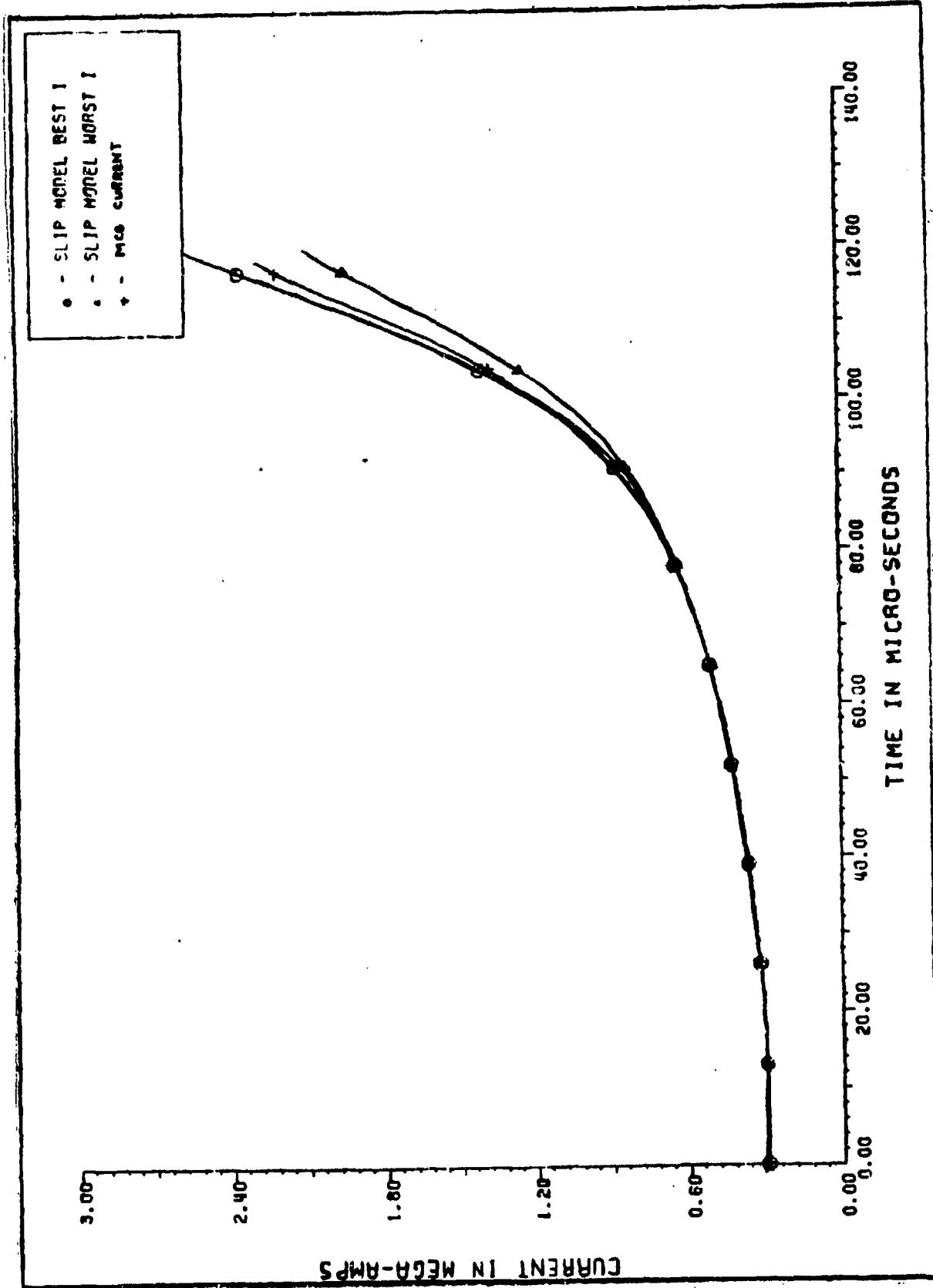


Figure B-15. Slipping Currents Test 2

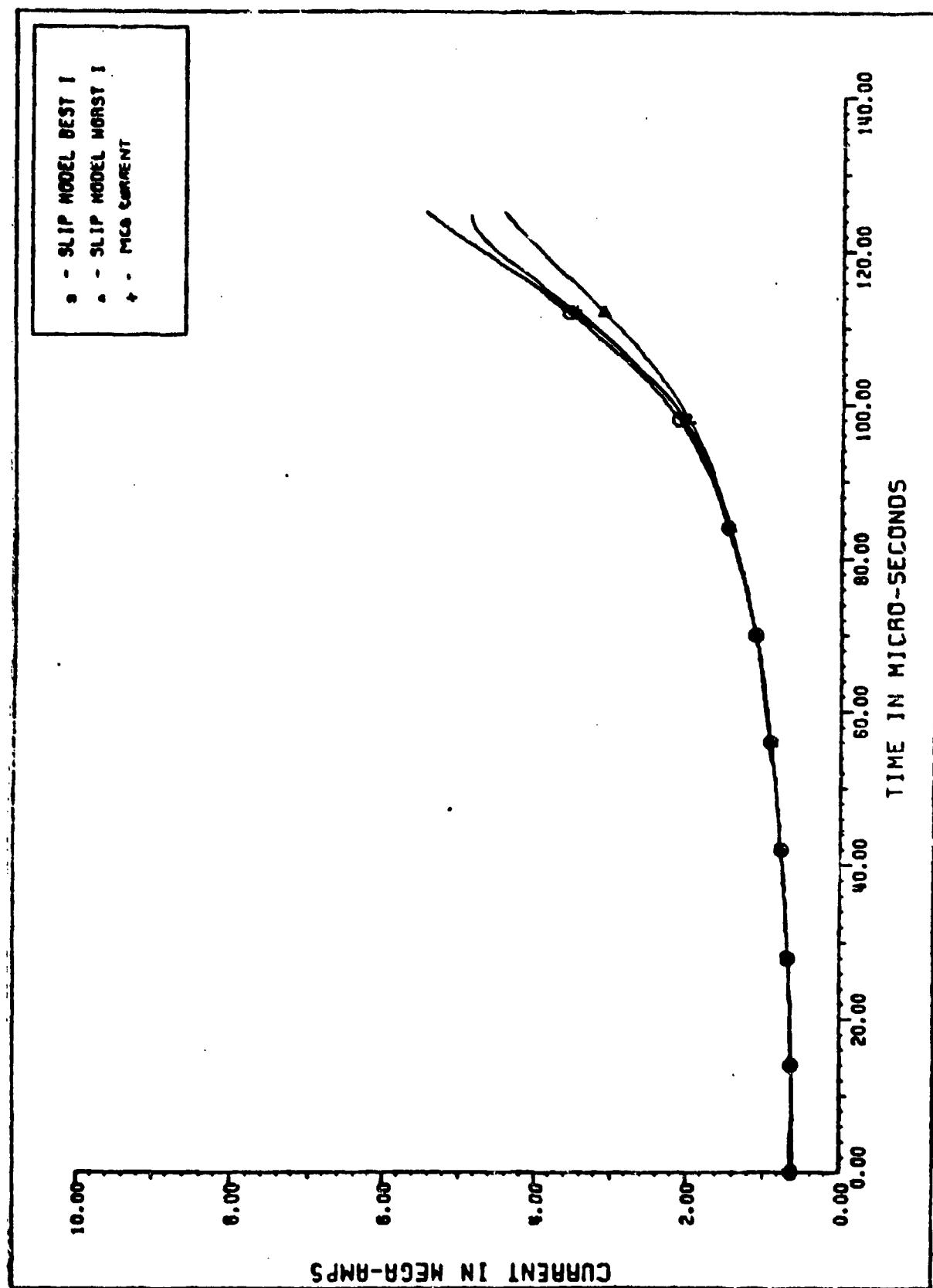


Figure B-16. Slipping Currents Test 3

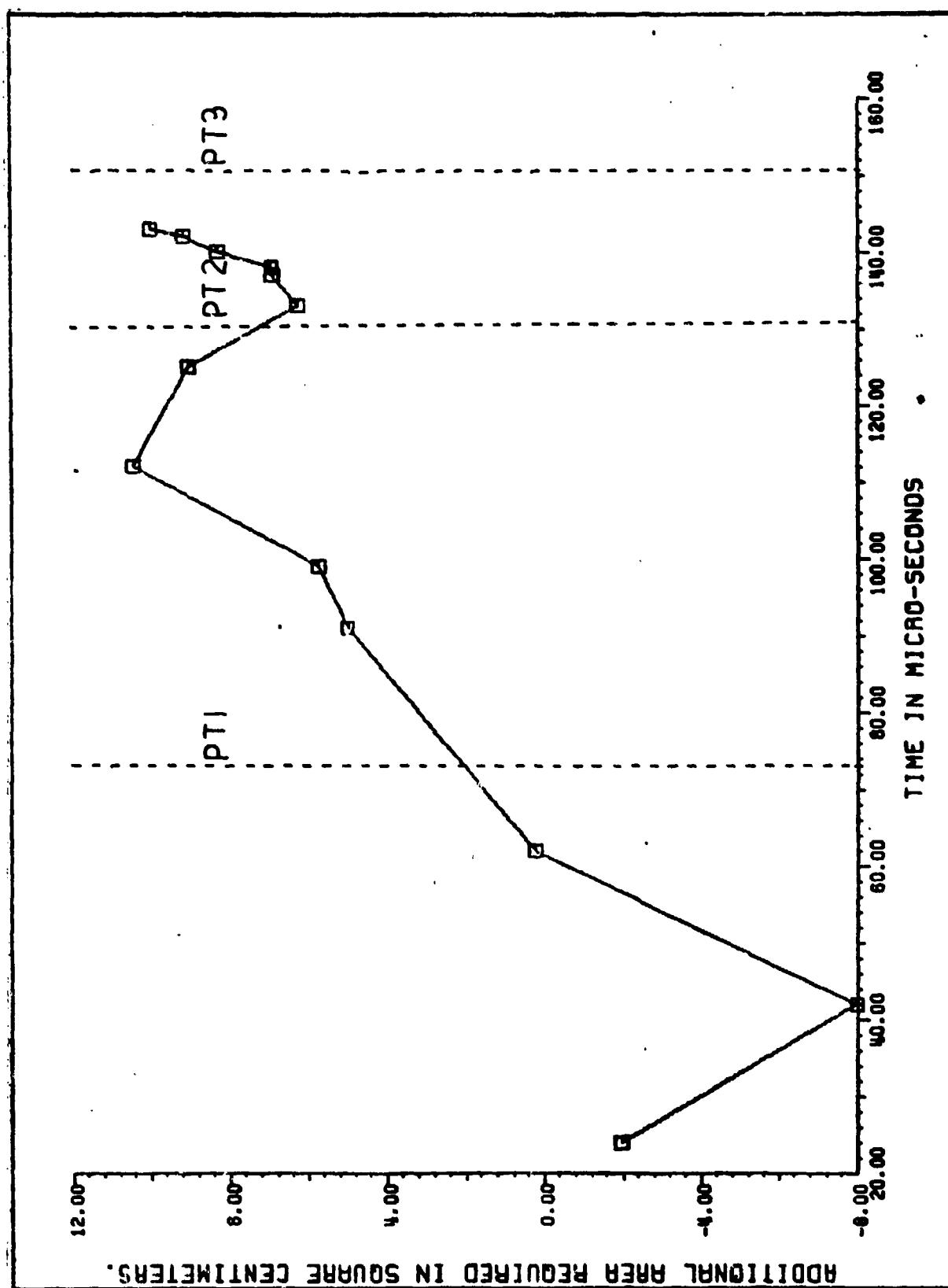


Figure B-17. Additional Area Test 2

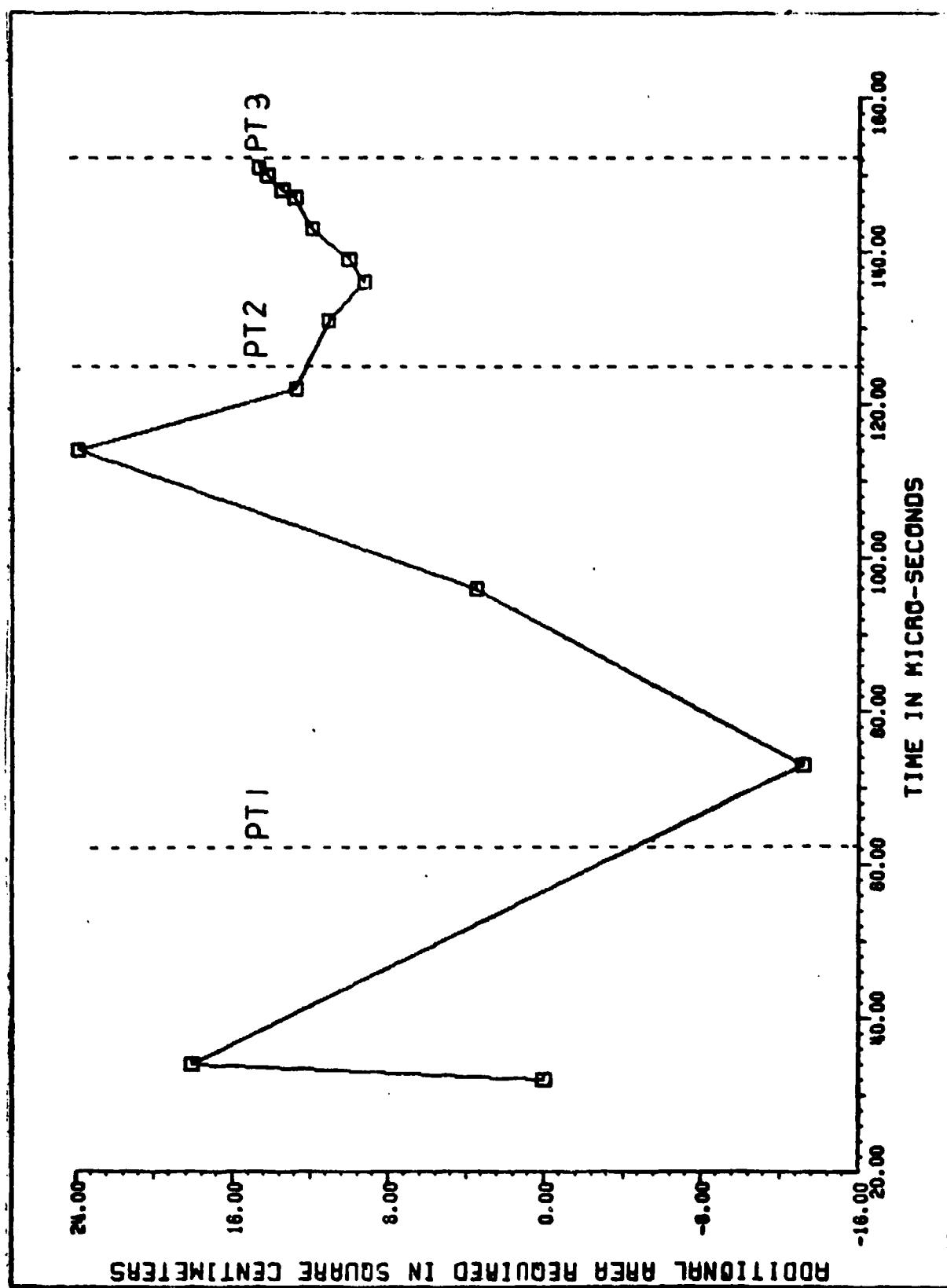


Figure B-18. Additional Area Test 3

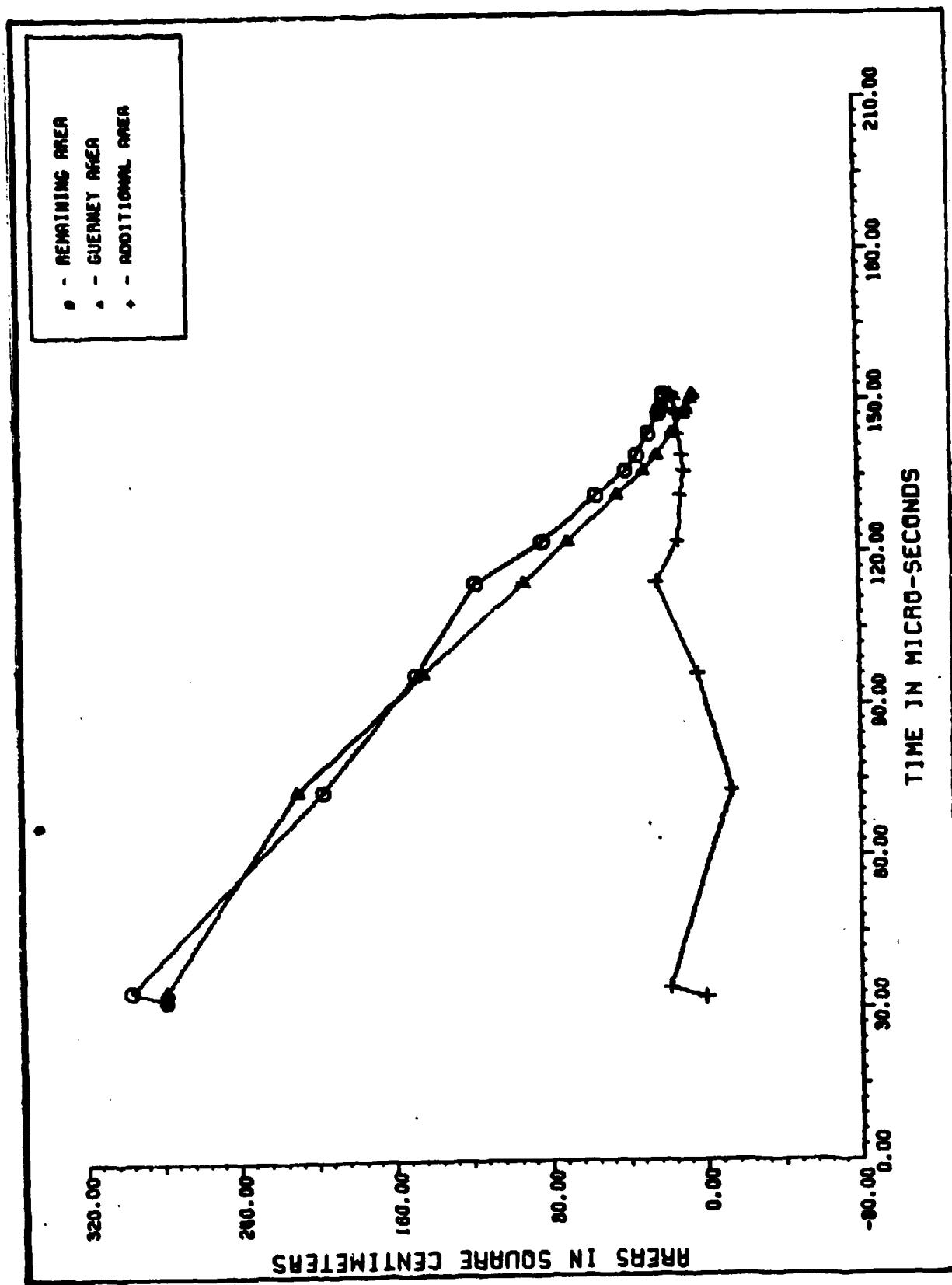


Figure B-19. Changing Areas Test 2

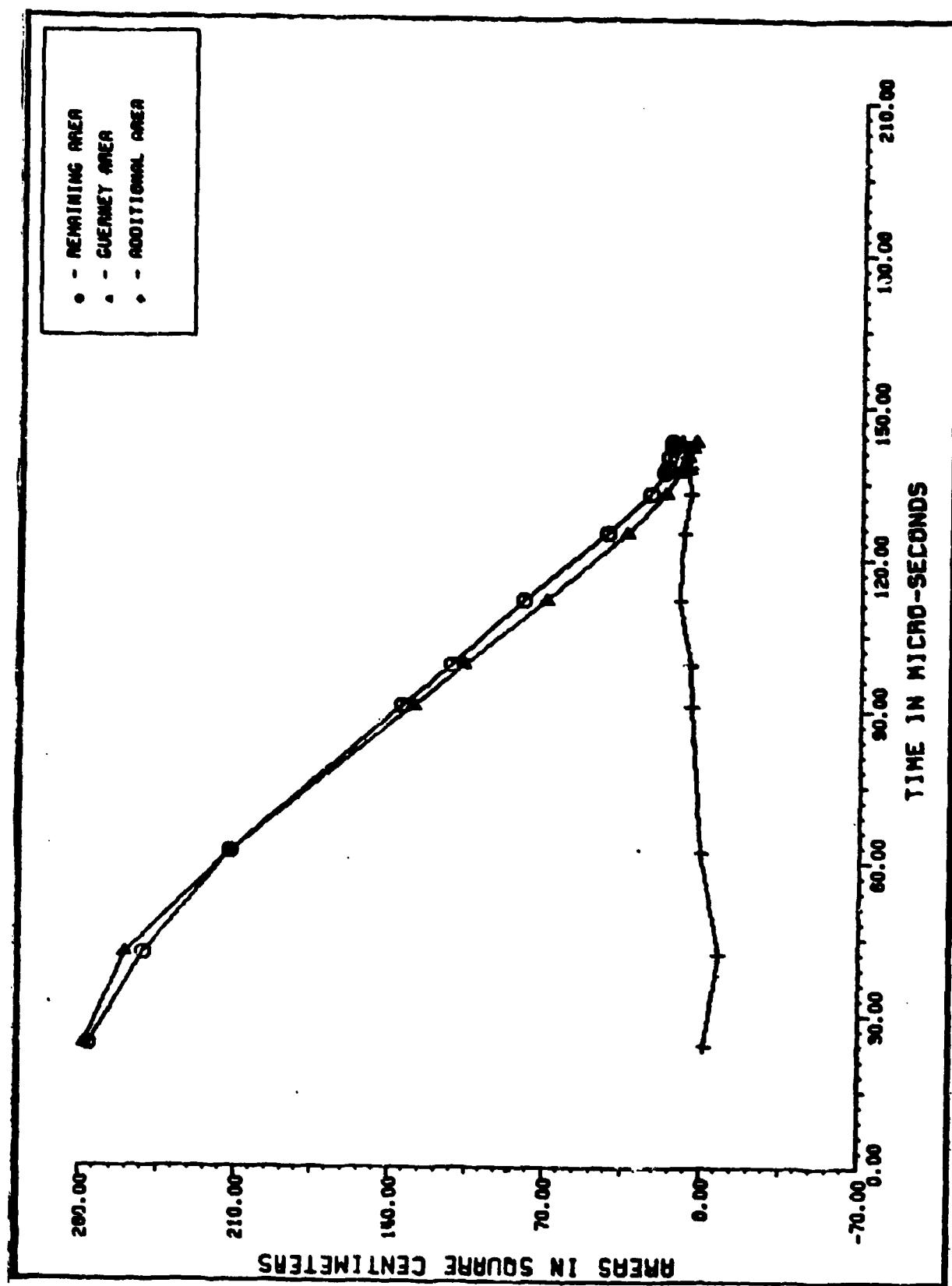
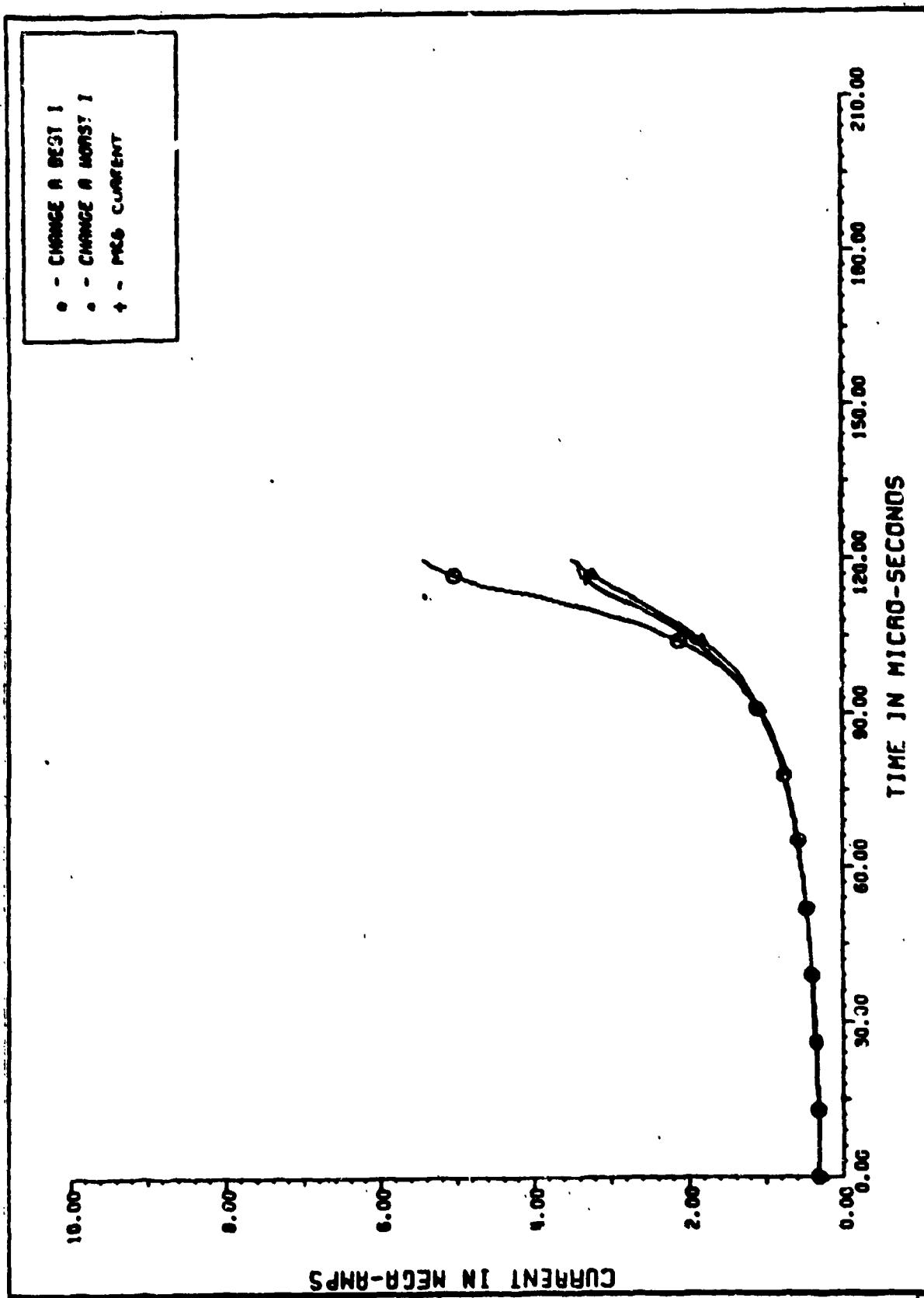


Figure B-20. Changing Areas Test 3



**Figure B-21.** Changing Area Currents Test 2

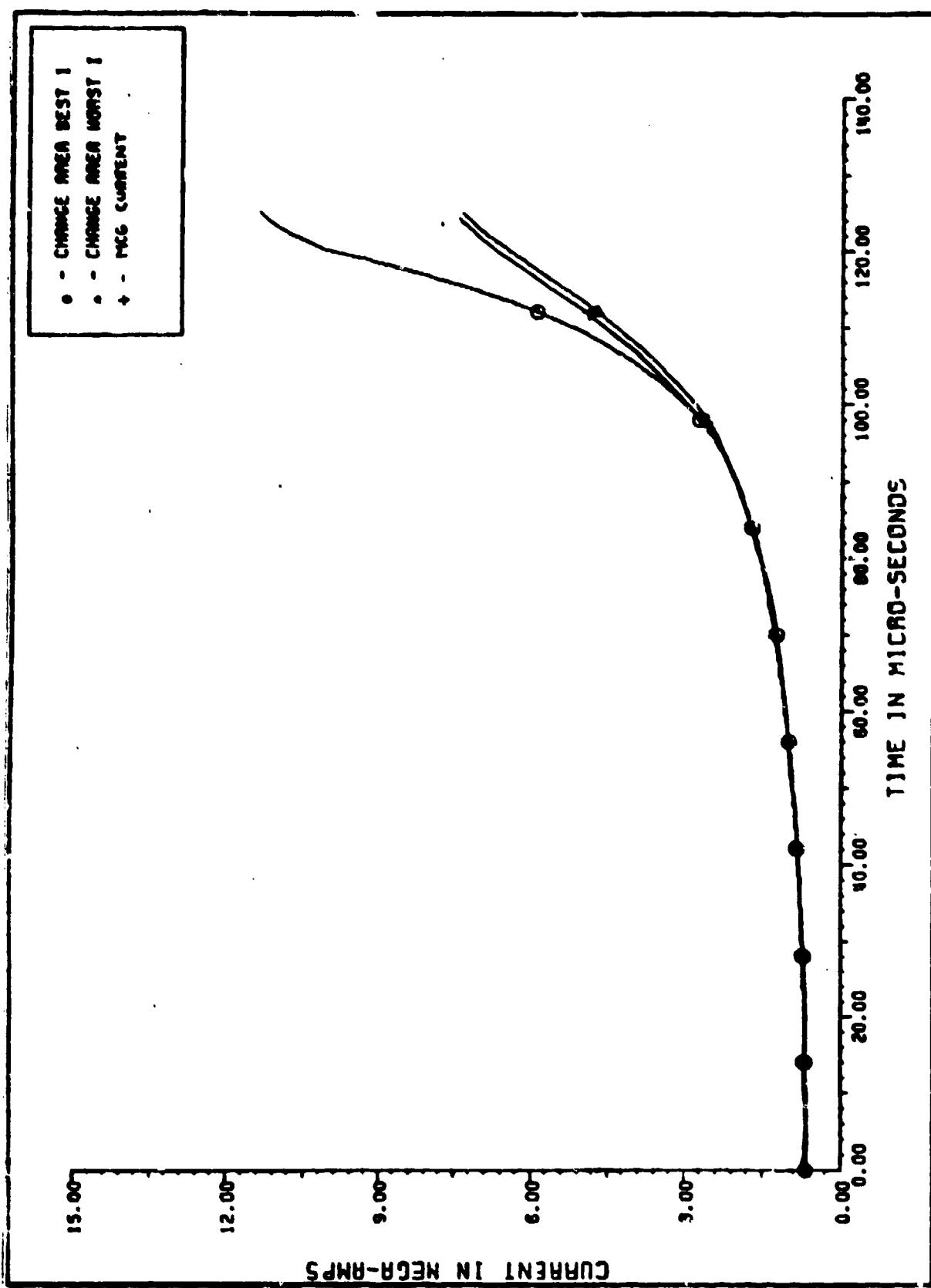


Figure B-22. Changing Area Currents Test 3

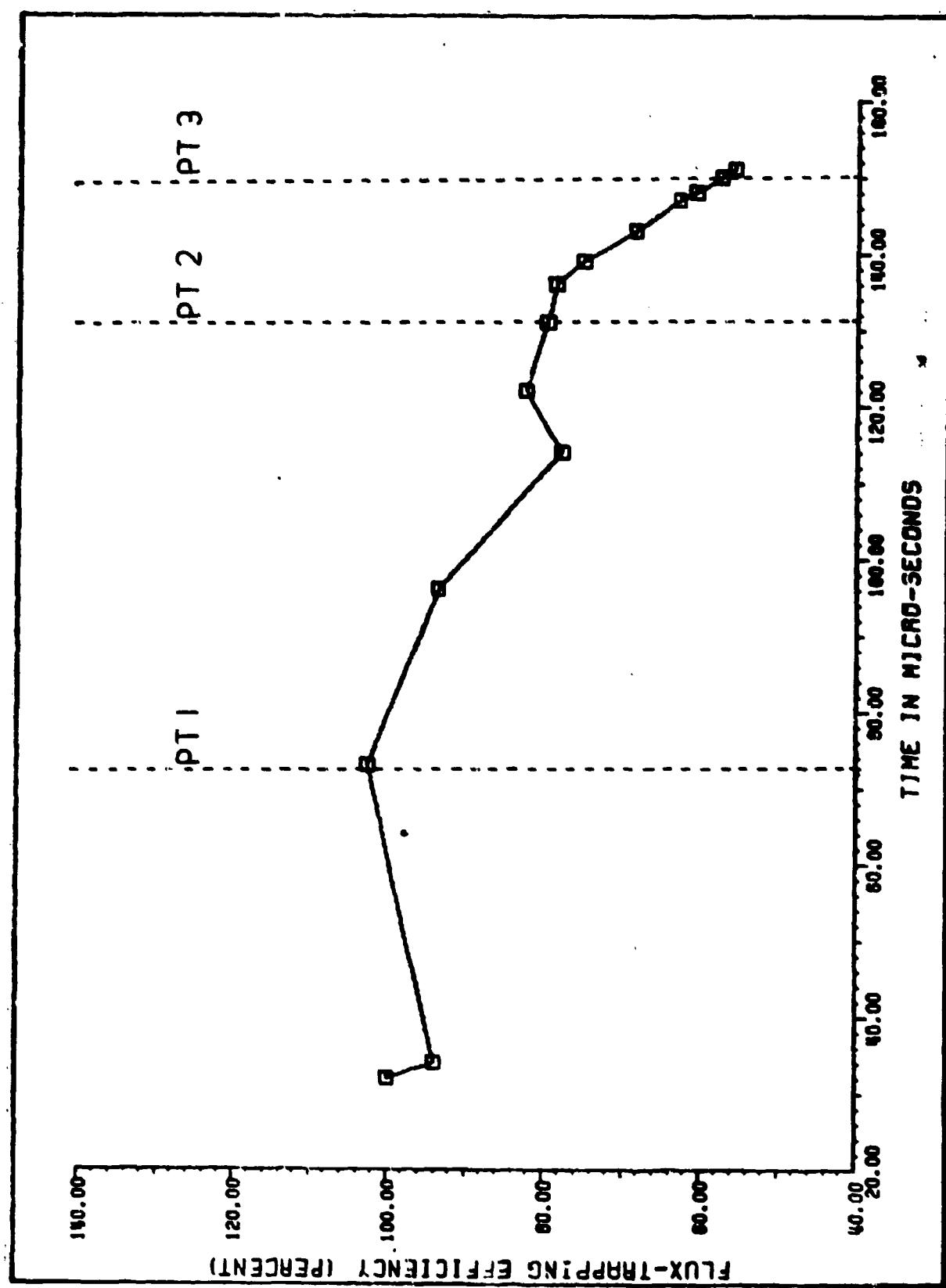


Figure B-23. Efficiency Test 2

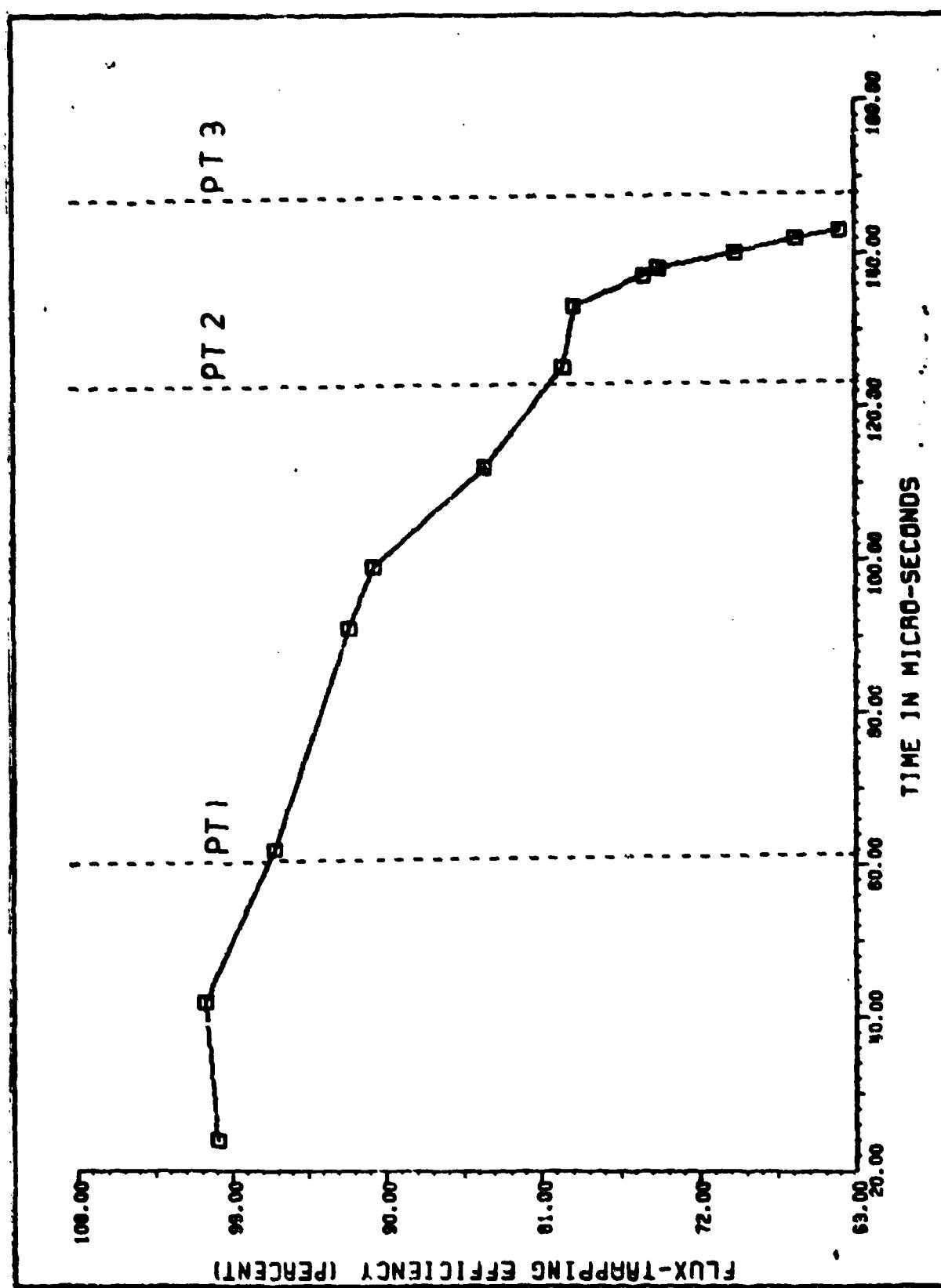
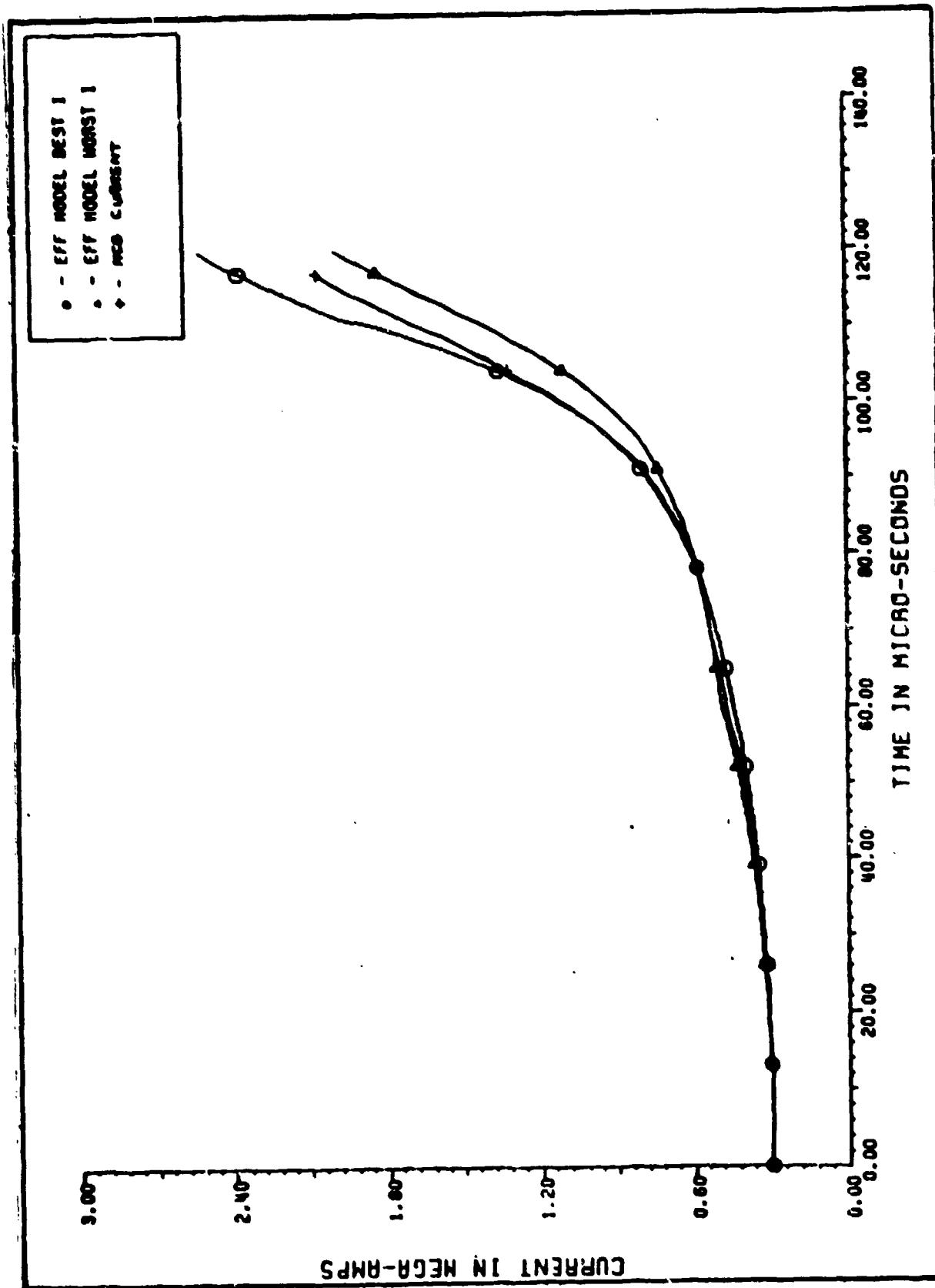
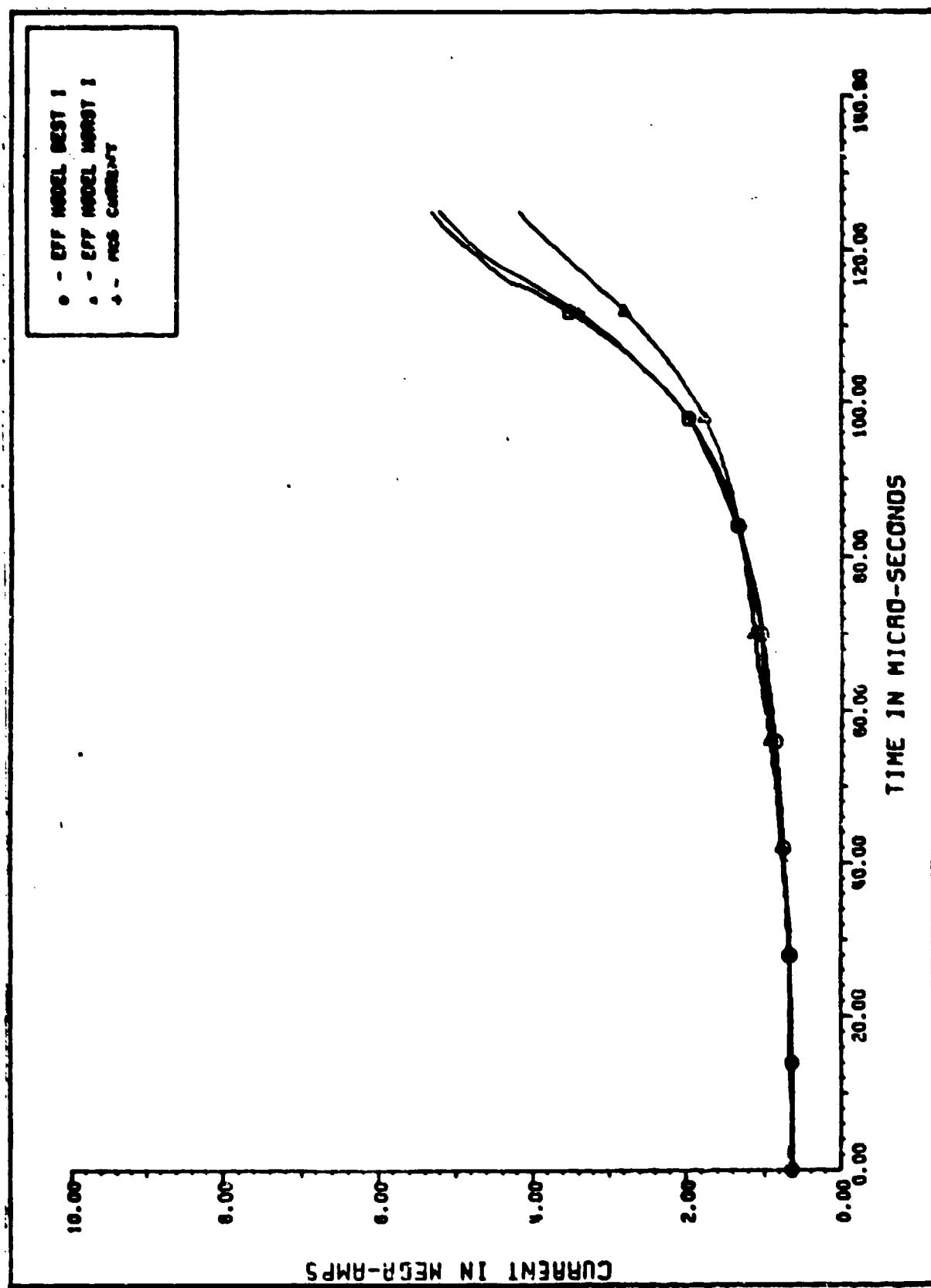


Figure B-24. Efficiency Test 3





## Bibliography

1. Knoepfel, Heinz. Pulsed High Magnetic Fields. New York, NY: American Elsevier Publishing Company, 1970.
2. Herlach, Fritz. "Flux Loss and Energy Balance in Magnetic Flux Compression Experiments," Journal of Applied Physics, 39, (11):5191-5204 (October 1968).
3. Reinovsky, Robert E., Research Physicist, Simulators and Advanced Weapons Concepts Branch, Kirtland AFB, New Mexico (personal correspondence), September 1983.
4. Plonsey, Robert and Robert E. Collin. Principles and Applications of Electromagnetic Fields. New York: McGraw-Hill Book Company, 1961.
5. Lehner, G., J. G. Linhart, and J. P. Somon. "Limitations on Magnetic Fields Obtained by Flux Compression I," Nuclear Fusion, 4, 362-379 (1964).
6. Kennedy, J. E. Gurney Energy of Explosives: Estimation of the Velocity and Impulse Imparted to Driver Metal. Sandia Laboratories Report No SC-RR-70-790, December 1970.
7. Gerasimov, L. S. and V. I. Ikryannikov. "Magnetic Accumulation in a Plane Liner of Finite Thickness," Soviet Physics Technical Physics, 23, (2):147-149 (February 1978).
8. Tucker, T. J. and B. N. Turnman. "Modeling and Scaling Experiments of Explosive Driven Pulse Power Systems," Proceedings of the Third IEEE International Pulse Power Conference: 334-336 (June 1981).
9. Lewin, J. D. and P. F. Smith. "Production of Very High Magnetic Fields by Flux Compression," Review of Scientific Instruments, 35, 541-548 (May 1964).
10. Herlach, F. "Megagauss Magnetic Fields," Reports on Progress in Physics, 31, 341-417 (1968).
11. Damerow, R. H., J. C. Crawford, D. B. Thomson, R. S. Caird, K. J. Ewing, W. B. Garn, and C. M. Fowler. "Use of Explosive Generators to Power the  $\theta$  Pinch," Symposium on Engineering Problems of Fusion Research: DI8-1-DI8-6 (1968).
12. Fowler, C. M., R. S. Caird, and W. B. Garn. An Introduction to Explosive Magnetic Flux Compression Generators. Los Alamos, New Mexico: Los Alamos Scientific Laboratory of University of California, March 1975 (Report LA-5890-MS).
13. Schwab, Adolf J. High-Voltage Measurement Techniques. Cambridge, MA: M. I. T. Press, 1970.

VITA

Mary Jeffrey

Mary Patricia Jeffrey was born 14 November 1954 in Milwaukee, Wisconsin. She graduated from high school in Kaukauna, Wisconsin in 1973. She entered the Air Force in 1973 and served as a communications specialist. In 1976 she entered the Air Force Academy and received the degree of Bachelor of Science in Electrical Engineering and an Air Force commission in 1980. She entered the School of Engineering, Air Force Institute of Technology in June 1982.

Permanent address: Mounted Route 8  
Box 145  
Cumberland Head  
Plattsburgh, New York 12901

James Hebert

James Leland Hebert was born on 29 June 1950 in Port Arthur, Texas. He graduated from Castle Heights Military Academy in 1968. He entered the Air Force in 1969 and served as a voice processing technician obtaining the rank of MSgt. Through AECP, he received a Bachelor of Science in Electrical Engineering from Texas Tech University in May 1982. Upon graduation, he attended OTS and received his commission in August 1982. He entered the School of Engineering, Air Force Institute of Technology in September 1982.

Permanent address: 3600 Lexington Avenue  
Port Arthur, Texas 77640

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE

## REPORT DOCUMENTATION PAGE

1a. REPORT SECURITY CLASSIFICATION UNCLASSIFIED		1b. RESTRICTIVE MARKINGS													
2a. SECURITY CLASSIFICATION AUTHORITY		3. DISTRIBUTION/AVAILABILITY OF REPORT Approved for public release, distribution unlimited													
2b. DECLASSIFICATION/DOWNGRADING SCHEDULE															
4. PERFORMING ORGANIZATION REPORT NUMBER(S) AFIT/GE/EE/83D-28		5. MONITORING ORGANIZATION REPORT NUMBER(S)													
6a. NAME OF PERFORMING ORGANIZATION Air Force Institute of Technology	6b. OFFICE SYMBOL (if applicable) AFIT/EN	7a. NAME OF MONITORING ORGANIZATION													
6c. ADDRESS (City, State and ZIP Code) Wright-Patterson AFB, OH 45433		7b. ADDRESS (City, State and ZIP Code)													
8a. NAME OF FUNDING/SPONSORING ORGANIZATION Air Force Weapons Lab	8b. OFFICE SYMBOL (if applicable) AFWL/RNAA	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER													
8c. ADDRESS (City, State and ZIP Code) Kirtland AFB, NM 87117		10. SOURCE OF FUNDING NOS. PROGRAM ELEMENT NO.      PROJECT NO.      TASK NO.      WORK UNIT NO.													
11. TITLE (Include Security Classification) See Box 19															
12. PERSONAL AUTHOR(S) Mary P. Jeffrey, 1Lt USAF      James L. Hebert, 2Lt USAF															
13a. TYPE OF REPORT	13b. TIME COVERED FROM _____ TO _____	14. DATE OF REPORT (Yr. Mo. Day) December 1983	15. PAGE COUNT 122												
16. SUPPLEMENTARY NOTATION Approved for public release; IAW AFR 190-17 Approved for public release; IAW AFR 190-17 LYNN E. WOLVER Dean for Research and Professional Development Air Force Institute of Technology (AFIT) Wright-Patterson Air Force Base (Block number) 7 Dec 84															
17. COSATI CODES <table border="1"><tr><th>FIELD</th><th>GROUP</th><th>SUB. GR.</th></tr><tr><td>10</td><td>02</td><td></td></tr><tr><td></td><td></td><td></td></tr><tr><td></td><td></td><td></td></tr></table>		FIELD	GROUP	SUB. GR.	10	02								18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number) Pulse Generator      Explosive Generator Electric Generator      Magnetocumulative Generator	
FIELD	GROUP	SUB. GR.													
10	02														
19. ABSTRACT (Continue on reverse if necessary and identify by block number)  Title: Computer Modeling and Experimental Validation of Losses in a Strip Geometry Explosive Magnetic Flux Compression Generator  Advisors: Major Timothy L. Skvarenina, AFIT/EN Dr. Robert E. Reinovsky, AFWL/RNAA															
20. DISTRIBUTION/AVAILABILITY OF ABSTRACT <input checked="" type="checkbox"/> UNCLASSIFIED/UNLIMITED <input checked="" type="checkbox"/> SAME AS RPT. <input checked="" type="checkbox"/> DTIC USERS <input type="checkbox"/>		21. ABSTRACT SECURITY CLASSIFICATION UNCLASSIFIED													
22a. NAME OF RESPONSIBLE INDIVIDUAL Mary P. Jeffrey, 1Lt, USAF		22b. TELEPHONE NUMBER (Include Area Code) 513-255-5533	22c. OFFICE SYMBOL AFIT/EN												

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE

A computer program to predict the performance of a strip geometry explosive magnetic flux compression generator (MCG) was developed and validated.

The program contains five separate models of the MCG, two theoretical and three empirically based. The first model is a theoretical lossless flux conserved model. The second model accounts for resistive losses due to plate resistance and a flux diffusion equivalent resistance. The first empirical model models the remaining losses as a slipping loss. The second empirical model adjusts the flux conserved model with an additional time varying inductance. The final empirical model is a simple flux trapping efficiency model.

Actual MCG experiments were conducted using the Air Force Weapons Laboratory's strip MCG. The data from these experiments was used to validate the computer program. Input currents varied from 294.0 KA to 1100.0 KA with resulting output currents of 2210.0 KA to 10261.0 KA and current amplification factors between 6.29 and 15.75.

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE